Ichnology, Sedimentology and Paleoenvironmental Reconstruction of the Lower Cambrian Addy Quartzite, northeastern Washington State, U.S.A.

A Thesis Submitted to the College of
Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in the Department of Geological Sciences
University of Saskatchewan
Saskatoon

By
Terri Linda Graham

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

DISCLAIMER

This thesis was exclusively created to meet partial requirements for the degree of Master of Science at the University of Saskatchewan. Reference in this thesis to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the University of Saskatchewan. The views and opinions of the author expressed herein do not state or reflect those of the University of Saskatchewan, and shall not be used for advertising or product endorsement purposes.
Requests for permission to copy or to make other uses of materials in this thesis in whole or part should be addressed to:

Head of the Department of Geological Sciences
University of Saskatchewan
Saskatoon, Saskatchewan S7N 5E2
Canada

OR

Dean
College of Graduate Studies and Research Room C180 Administration Building, 105 Administration Place University of Saskatchewan Saskatoon SK S7N 5A2

Abstract

The Addy Quartzite is a tide-dominated shallow-marine unit of heterolithic nature found in northeast Washington State. The Addy is Early Cambrian in age and reflects sedimentation during a global transgression along the paleocoast of the North American Craton. Due to a lack of previous integrated ichnologic, sedimentologic and paleoenvironmental data, an evaluation of all ecological aspects during deposition of the Addy Quartzite has not been provided until now. Twelve sedimentary facies, grouped into five facies associations were found within the Addy Quartzite. The sedimentary data clearly shows the establishment of a compound-dunefield. Eleven trace fossils, grouped into six trace fossil assemblages, linked with a sedimentary facies association, were found within the Addy Quartzite. The ichnologic data indicates a diverse and well-established climax community inhabited both the compound-dune bottomsets and interdune areas, and an opportunistic community consisting dominantly of trace fossils reflecting suspension-feeding organisms is favoured in the 2D and 3D dunes of the compound-dune field. The ichnologic data also adds information on the evolutionary paleoecology during the time of Addy deposition, allowing for a more clear designation of the importance of tide-dominated shallow-marine settings and their role in hosting the benthic fauna of the Cambrian agronomic revolution. The Addy Quartzite provides new insight into the evolution of benthic communities along the paleocoast of the North American Craton during the Early Cambrian.

Acknowledgements

I would like to acknowledge the support and guidance of my graduate supervisor Dr. M. Gabriela Mangano. Special thanks to Dr. Elizabeth Nesbitt for bringing this project to my attention and allowing me to take it on as my graduate work. I would also like to thank the head of the department of geological sciences Dr. Jim Merriam as well as the members of my advisory committee Dr. Luis Buatois and Dr. Elizabeth Robertson. I must also thank my field assistants Barry Graham and Meagan Gilbert for their many hours of physical labour in the hot sun. This project was partially funded by the Eva Saffian Memorial scholarship, and the department of Geological Sciences Teaching assistantship.

Table of Contents

Permission to use i

Abstract ii

Acknowledgements iii

Table of Contents iv

List of Tables v

List of Figures.....…v

List of Plates……v

1 Introduction

1.1 Previous Work……...….1

1.2 Research Objectives…….....2

1.3 Significance of Arthropod Trace Fossils……...….2

1.4 Arthropod Anatomy……3

1.5 Trilobite Traces……...4

2 Geologic Framework……...……..5

2.1 Body Fossils of the Addy Quartzite……...6

2.2 Field Location……8

3 Sedimentology

3.1 Methodology……..9

3.2 Facies……...……..9

3.3 Facies Associations……..……11

4 Trace Fossils

4.1 Methodology…….…..19

4.2 Ichnotaxonomy……...19

4.3 Trace Fossil Assemblages……..31

5 Arthropod Trace Fossils in the Addy Quartzite…….……...33

6 Trace Fossils and Biostratigraphy……34

7 Evolutionary Paleoecology of the Addy Quartzite……...34

8 Conclusions……...35

References……37

List of Tables

Table 2.1- Body Fossils of the Addy Quartzite…….……..7

Table 3.1.Sedimentary Facies of the Addy Quartzite…….10

Table 3.2. Facies Associations of the Addy Quartzite……18

List of Figures

Figure 2.1. Field localities 1 through 4. Outcrops and collection sites of the Addy Quartzite in Stevens County, northeast Washington State, USA……...…8

Figure 3.1. Stratigraphic section of the upper unit of the Addy Quartzite at the Addy Roadcut, Parker Mountain Roadcut and Wrights Mountain Roadcut, northeast Washington State…….....12

Figure 3.2 Facies Association 1……..13

Figure 3.3 Facies Association 2……..14

Figure 3.4 Facies Association 3……..15

Figure 3.5 Facies Association 4……..16

Figure 3.6 Facies Association 5……..27

List of Plates

Plate 1. *Rusophycus pecinatus*……28

Plate 2. *Cruziana pectinata, Rusophycus jenningsi* and *Cheiichnus gothicus*……29

Plate 3. *Helminthopsis hieroglyphica, Planolites montanus* and *Palaeophycus tubularis*……...29

Plate 4. *Skolithos linearis* and *Halopoa* isp……...30

Plate 5. *Dactyloidites asteroides* and cf. *Asterosoma* isp……..30

1 Introduction

1.1 Previous Work on the Addy Quartzite

Earliest research, involving the Early Cambrian Addy Quartzite as a formal unit, resulted in a Washington Geological Survey manuscript by Charles E. Weaver (1920). Weaver was the first to formally describe the geographic extension, lithology and structure of the unit that crops out in Stevens and Pend Oreille counties, northeastern Washington State, . U.S.A.. The next work on the Addy Quartzite was a series of reports, from the 1940's to the 1980's, by the United States Geological Survey and the Washington Division of Geology (Bennett, 1941; Park and Cannon, 1943; Campbell and Loufburrow, 1962; Miller and Clark, 1975; Evans, 1987). Most of the early reports were focused on determining the economic importance of the Addy Quartzite and other units in Stevens and Pend Oreille Counties (Bennett, 1941; Park and Cannon, 1943; Campbell and Loufburrow, 1962). Subsequent government publications involving the Addy quartzite dealt with lithologic description and stratigraphy (Miller and Clark, 1975; Evans, 1987). In the late 1980's and early 1990's, Kevin Lindsey, David Gaylord and Louis Groffman collaborated on three papers (Lindsey et al., 1988, 1990; Lindsey and Gaylord, 1992). These papers focused on the sedimentology of Early Cambrian sedimentary units in northeastern Washington, the Three Sisters Formation, the Gypsy Quartzite and the Addy Quartzite.

A scant two publications have been published over the last six decades, on the paleontology of the Addy Quartzite (Okulitch, 1951; Dutro and Gilmour, 1989). Dutro and Gilmour (1989) focused on the biostratigraphy of northeastern Washington from the earliest Paleozoic to the Lower Triassic. Their research suggests that the Gypsy Quartzite, also from northeast Washington, is coeval with the Addy Quartzite. The research presented by Vladimir Okulitch (1951) described a sparse fossil assemblage which includes archaeocyathids, brachiopods (*Micromitra, Kutorgina* and *Rustella*), and a trilobite (*Nevadella addyensis*). It is the presence of the trilobite *N. addyensis,* described by Okulitch (1951), as a characteristic middle Early Cambrian genus that confirms the age of the Addy Quartzite. The paleontological content of the Addy Quartzite suggests a faunal affinity with the Gypsy Quartzite of northeastern Washington State, the Reno and Quartzite Range Formations in southeast British Columbia, and more speculatively with the Hamill series of British Columbia. Specifically, the presence of *Nevadella addyensis* indicates a Cambrian age, Waucoban series, Montezuman stage, Nevadella biozone , corresponding to approximately 515 to 520 mya (Hollingsworth, 2005).

No papers have been published solely on the ichnology of the Addy Quartzite, although Okulitch (1951) and Lucas (1980) mentioned it. Ichnofossils mentioned in these papers are referred to as "fucoids" and "burrows" by Okulitch (1951) and as *Skolithos* and *Planolites* by Lucas (1980). Ichnofossils are also briefly mentioned by Lindsey et al., 1990, referring to the presence of *Rusophycus* in the upper unit near the location of the Addy Roadcut.

1.2 Research Objectives

The purpose of this research is to: (1) describe the facies associations of the Addy Quartzite, and interpret them in terms of depositional processes; (2) reconstruct the sedimentary environments along the western edge of the Wyoming Craton during the Early Cambrian; (3) provide the first detailed systematic study of the ichnofossils present in the Addy Quartzite; (4) define trace-fossil assemblages, and relate them to particular environmental controls and ichnofacies; and (5) explore the paleoecological and evolutionary significance of the Addy ichnofauna. Past work has overlooked the significance of trace fossils and how they can help in providing a more in depth understanding of life in this early Phanerozoic shallow-marine setting. Facies are characterized in an attempt to better understand the environmental setting inhabited by the Addy Quartzite biota. This research then couples sedimentologic and ichnologic datasets to effectively provide a robust characterization of the paleoecological and paleoenvironmental setting along the western margin of the Wyoming Craton during this time of the Cambrian.

1.3 Significance of Arthropod Trace Fossils

Arthropod trace fossils have received considerable attention because of the important ecological role that arthropods have had in the evolution of life on Earth. Arthropod trackways, trails, and burrows are known throughout the history of animal life on Earth, from the Cambrian to the present. A wide variety of arthropod trace structures, particularly cruzianids related to trilobite and trilobitomorph activities, are dominant in Cambrian-Ordovician shallow-marine successions (Mángano and Droser, 2004). Arthropod structures are quite complex in morphology providing information on locomotion mechanisms and the behaviour involved. The phylum Arthropoda has a privileged position in the history of life on Earth due to the fact that it is the most numerous phyla in terms of number of individuals and number of species (Pechenik, 2005). Arthropod trackways are unique in that they are produced by undertrack preservation, generated on thinly laminated sands and silts or eolian dune sands, mostly in damp or wet substrates (Seilacher, 2007). These requirements affect the potential for preservation, and as such arthropod trackways are under represented in the trace-fossil record (Seilacher 1985, 1994). Preservation can also be affected by locomotory behaviour. Although arthropods generally have continuous leg support, gait variations such as hopping, current drifting, lateral offset and sidleing can affect the appearance of the trace left behind (Seilacher, 2007). However, arthropod burrows or nesting structures typically have a high preservation potential, and as such are well represented throughout the history of animal life (Seilacher, 2007).

Arthropods are so named for their jointed appendages, which can be highly differentiated in some clades based upon the function they perform (Pechenik, 2005). In the earliest Paleozoic the

most useful and important arthropod trace fossils are those created by trilobites or trilobitomorphs, due to their abundance and distinctive morphology. The complexity of trilobite trails and the precision with which they can be identified makes cruzianid type trace fossils extremely useful in correlation of otherwise unfossiliferous sandstone units in particular (Seilacher, 1970, 1990, 1994). Due to this precision, a well-established Cambrian-Ordovician ichnostratigraphic paradigm was conceived and modified by many authors (Crimes, 1968, 1969; Seilacher, 1970; Crimes 1975; Moreno et al., 1976; Crimes and Marcos, 1976; Baldwin, 1977, 1978; Pickerill et al., 1984; Romano, 1982; Pickerill and Fillion, 1989; Magwood and Pemberton, 1990). After the Paleozoic, non-trilobite cruzianid traces become of more limited use, although other arthropod structures are important components in marine (e.g. crustacean burrows) and terrestrial (e.g. insect nests) environments (Bromley, 1996).

1.4 Arthropod Anatomy

Members of the phylum Arthropoda share some common anatomical features which have become variously modified depending upon the animals' ecological role within its environment (Pechenik, 2005; Seilacher, 2007). The arthropod body is covered by a segmented external skeleton made of chitin, protein and polysaccharides (Pechenik, 2005; Seilacher, 2007). The arthropod body is divided into a head segment, a thorax and the abdomen or pygidium which house the waste organs (Pechenik, 2005). Arthropods are known for jointed appendages. These appendages are differentiated based upon the function they provide such as sensory appendages, locomotory appendages and mouth parts (Seilacher, 2007).

Perhaps the most conservative anatomy of the Paleozoic arthropods is that of trilobites (Manton, 1977). This anatomy leads to unique expressional variations in terms of the trace fossils they leave behind. Trilobites have biramous appendages down the entire length of their bodies, a single set of antennae and the body carapace is dorso-ventrally flattened.

Of the few well-preserved trilobites available the undifferentiated mouth parts consist of a small, minerally reinforced, opening that Seilacher (2007), inferred was used to ingest particulate matter by an expanding intestinal chamber moved by radial muscles and ligaments. Particles would be moved towards the anterior mouth by a mid-line water current generated by the head-ward metachronal leg movement. In this model trilobites were likely dominantly detrital feeders, some may have developed a carnivorous lifestyle (Fortey and Owens, 1999). The biramous appendages are themselves differentiated with an outer branch, the exopodite (also telopodite), used for ventilation and sieving food particles and an inner branch, the endopodite (also endite), used for walking and burrowing (Bergström, 1969; Seilacher, 1985, 2007). The exopodite is a delicate structure with many setae for straining and entrapment of food particles and would have also been used, albeit to a lesser extent, for locomotion. The exopodite produces fine brushing like structures along the outer margins of trilobite trails and resting traces. The endopodite contains setae along the proximal gnathobase and towards the distal tip, these setae would create

the fine details on the substrate that can be observed as typical ornamentation of trilobite trace fossils and have been characterized in the ichnologic literature as “the claw formula” (Seilacher, 1985, 2007).

1.5 Trilobite Trace Fossils

Trilobite trace fossils are of particular interest in Palaeozoic because their abundance, diversity and preservation of fine morphologic details that allow the reconstruction of the burrowing technique. Trilobite trace fossils seem to increase in complexity, in terms of efficiency in using the undifferentiated limbs, through the Palaeozoic. Trilobite trails decrease in dominance, which is directly coincidental with trilobite evolutionary history and their subsequent extinction at the end Palaeozoic. With the head-ward metachronal leg motion and much overstepping trilobite traces have an overlapping feature of appendage scratch marks which can obscure the trace to some extent. However, this leg motion also makes it easy to determine in which direction the animal was travelling and may aid in separating sets of appendage markings. Other body parts, besides the obvious endopodites, may also be present in trilobite traces, such as the fine brushings of the exopodites, cerci at the rear of the animal, the cephalon, genal or pleural spines and the gnathobases of the appendages; all serve to increase the complexity and thereby improve the precision with which each trace can be identified and ichnotaxonomically designated.
Trilobite trace fossils are generally made at, or near, the sand/mud interface, with an overlying loose sand layer and an underlying fine grained, firm substrate which preserves them as an undertrack duplicate (Crimes, 1975; Seilacher, 1970, 1994, 2007). Due to the nature of the preservation, these types of biogenic structures have a high fossilization potential (Seilacher, 1970, 2007). Preservation of trilobite traces is dominantly as positive hyporeliefs but depends upon the locomotive and behavioural intent of the organism. Trilobites produce a number of different ethological trace fossil types. Examples of repichnial trilobite structures include the ichnogenera *Diplichnites, Dimorphichnus* and *Monomorphichnus*. Examples of pascichnial trilobite trails include the ichnogenus *Cruziana*. Examples of cubichnial trilobite structures, generally interpreted as nests include the ichnogenera *Rusophycus* and *Cheiichnus*. Trilobite trace fossils are generally made at or near the sand/mud interface, with an overlying loose sand layer and an underlying fine grained, firm deposit which preserves as an undertrack duplicate (Crimes, 1975; Seilacher, 1970, 1994, 2007). Due to the nature of the preservation, these types of biogenic structures have a high fossilization potential (Seilacher, 1970, 2007).
Positive hyporelief pascichnial trails included in the ichnogenus *Cruziana* show a major activity of the trilobite lifestyle. Following Seilacher’s (1964) preservational classification, this would have provided the host with protection from predation and the environment, as well as providing access to food, such as other organisms (Jensen, 1990) or detritus (Seilacher and Pfluger, 1994). Thus, the combined movement and feeding implications require that *Cruziana* falls into pascichnia or grazing trails, in the ethological classification (Seilacher 1953a, 1964). The

attribution of these trails to trilobites is based upon environmental factors, time ranges, evolutionary history, morphology, mortichnial occurrences, and organism size range (Seilacher, 2007). Endopodal claw marks are the most important aspect of these traces, in terms of ichnotaxonomic classification and further the use of cruzianids in ichnostratigraphy (Crimes, 1975; Seilacher, 1994, 2007). The number, the relative position, and the shapes of the marks give information on the possible type/group of trilobites that could be the producer of the trace (Seilacher, 1994). Exopodite brushings are also important in terms of identifying trilobite trails (Seilacher, 2007). Although not the primary branch of the appendage used in trail making, the exopodites could become involved in some aspects of trail excavation, particularly along the outer margins of the burrow (Seilacher, 1994, 2007). They can aid in increasing the precision with which a high degree of distinction can be achieved in ichnotaxonomic identification down to the ichnospecific level (Seilacher 1970, 1990, 1994). Accessory skeletal elements may be involved in the trail making process, such as the cephalon, genal spines and cerci, which further increase precision of identification (Crimes, 1975; Seilacher, 2007).
Cubichnial trilobite burrows included in the ichnogenus *Rusophycus* are coffee-bean to heart shaped. They represent a onetime disturbance of the sediment from burrowing. They are also, like the ichnogenus *Cruziana*, dominantly found as positive hyporeliefs. The attribution of these trails to trilobites is based upon environmental factors, time ranges, evolutionary history, morphology, mortichnial occurrences and organism size range (Seilacher, 2007). Throughout the Paleozoic there is a general increase in the complexity of the morphology of rusophycid trace fossils due to anatomical modification which was utilized to increase the efficiency of sediment processing (Seilacher, 1994). Endopodal claw marks tend to be the most important feature in these traces as, the number, the relative position, and the shapes of the marks all give information on the possible type/group of trilobites that could be the producer of the trace (Crimes, 1975; Seilacher, 1994, 2007).

2 Geologic Framework

The Addy Quartzite is one of many Lower Cambrian units of western North America. The formation crops out in Stevens and Pend Oreille counties in northeastern Washington State, U.S.A (Park and Cannon, 1943; Dutro and Gilmour, 1989; Lindsey et al., 1990). The unit records deposition under shallow marine conditions along the western edge of the Wyoming Craton along a post-rift passive margin (Lindsey et al., 1988), during the Sauk global transgression. Deposition was continuous from Late Proterozoic to Early Ordovician times (Lindsey et al., 1988). Near the end of the highstand systems tract, terrigenously derived sand supply was cut off, and by the latest Early Cambrian a carbonate depositional system came to dominate in most of what is now northeast Washington State. The Addy is conformably overlain by the Maitlen Phyllite and Metaline Limestone (Lindsey et al., 1990). The Addy Quartzite, named by Charles Weaver in 1920, is up to 1400 m thick (Lucas, 1980; Evans, 1988). Correlatives include the

Gypsy Quartzite near Metaline Falls, Washington (Campbell and Loufburrow, 1962), the Quartzite Range near Salmo, British Columbia (Becraft and Weis, 1963), the Hamill Group near Nelson, British Columbia (Reesor, 1957), the Gog Group near Lake Louise, British Columbia (Mansy and Gabrielse, 1978), and the Brigham Group in southeastern Idaho and northern Utah (Lindsey et al., 1990). The Addy is laterally extensive and forms one of the most distinctive units in northeast Washington (Park and Cannon, 1943; Lindsey et al., 1990), with the best exposures in central and southern Stevens County, near the towns of Addy and Chewelah, Washington.
The collisional tectonics and compression which affected the western edge of the North American Craton during the Mesozoic produced three phases of folding, faulting and metamorphism (Lindsey et al., 1988, 1990). As such, the Addy Quartzite is highly folded into anticlines and synclines which generally host axis oriented at 5-10 degrees N-NW. The Addy Quartzite never exceeds green schist facies metamorphism, and the more southerly exposures of the unit become progressively less affected by metamorphism (Lindsey et al., 1990), sedimentary facies and trace fossils are, therefore, relatively well preserved.
The Addy Quartzite is an 1100-1450 m thick succession of quartzite, siltite and argillite, is divided into four units: (1) the basal unit, (2) the purple banded unit, (3) the coarse unit, and (4) the upper unit (Weaver, 1920). Lithology of the Addy was described by Weaver (1920) as, "massive, hard, crystalline, light coloured quartzite, minor quartz-mica schists, banded slates and mica-banded quartzites." Unfortunately, a complete section of the entirety of the formation cannot be located and measured, due to the intense folding and faulting of the area (Lindsey et al., 1990), and both vegetation coverage and private property/limited access. The basal unit of the Addy Quartzite is a fine- to medium-grained, mature quartzite, less than 200 m thick, with planar and trough cross-beds (Weaver, 1920; Evans, 1988; Lindsey et al., 1990). The purple banded unit forms a distinct horizon of medium- to coarse-grained quartzite with lenticular beds of purple siltite, less than 350 m thick with planar cross bedding and parallel stratification (Weaver, 1920; Lindsey et al., 1990). The coarse unit is composed of coarse-grained to granular quartzite, about 500 m thick, with planar-, herringbone- and trough-cross bedding (Evans, 1987; Lindsey et al., 1990; Weaver, 1920). The upper unit consists of interbedded quartzite, silltite, and argillite, about 500 m thick, with wavy quartzite beds showing planar and herringbone cross bedding, and ripple-cross lamination (Weaver, 1920; Lindsey et al., 1990).
A section of approximately 100 m of the upper interval of the Addy Quartzite will be discussed in detail in this thesis.

2.1 Body Fossils of the Addy Quartzite

The Addy Quartzite contains a low-diversity assemblage of body fossils. These fossils are very poorly preserved, and occur primarily as molds and casts with no original shell material. Trilobites and hylothids are the numerically dominant taxa. Poor preservation makes it difficult to distinguish numerous disassociated shell debris that has a narrow curved shape and may be

trilobite genal spines or hylothid helens. Brachiopods are common on some bedding planes. Bioturbation has diminished their numbers and it is uncertain if this is relative rarity or a taphonomic feature. Low-level metamorphism is a factor with the preservation of body fossils in the Addy Quartzite, obscuring a clear picture of the exact fauna present in the unit. Table 2.1 reports the known body fossils from the Addy Quartzite and their abundances.

Table 2.1- Body Fossils of the Addy Quartzite

Trilobites	Comments
Nevadella addyensis (Okulitch 1951)	Most common trilobite. Material is as impressions of the furrow and some genal spines. There are very few complete specimens, and distortion is common.
Grandinasus argentus (Walcott, 1910)	Very rare (see Hollingsworth, 2006).
Hylothida	
Nevadothesca whitei (Ressler, 1938)	Most common hylothid.
Hyolitha sp.	Very rare. Lack of detail prevents a definitive species name.
Brachiopoda	
Obolella excelsis (Walcott) 1908	Most common brachiopod but all very poorly preserved.
Kurtorgina cingulata (Billings) 1861	Second most common brachiopod taxa.
Unidentifiable lingulid	Rare
sponges	An abundance of sponge remnants are present but remain unidentifiable.

2.2 Field Location

The study area for this investigation is located near the towns of Addy and Chewelah, in northeastern Washington State, United States (Figure 2.1). All collecting localities are labelled 1to 4 on the map. Field locality 1 is the Addy Roadcut: it is the main source of stratigraphic and detailed sedimentologic data compiled in this thesis. This road cut is directly west of the town of Addy, near and inside the private boundaries of the recently decommissioned mine belonging to Northwest Alloys Inc. The roadcut is approximately 90 m thick with a 10 m section that is covered by vegetation. Field locality 2 is the Parker Mountain Roadcut: southeast of the town of Chewelah, near Sherwood Creek. This roadcut exposes almost vertical beds showing a section nearly 83 m thick with a 10 m section that is unmeasureable due to vegetation cover and heavy erosion. Field locality 3 is the Wrights Mountain roadcut: southwest of the town of Chewelah, along Wrights Valley Road. The roadcut preserves a section nearly 35 m thick with a further 12.5 m section covered by vegetation. Field locality 4 is Stensgar Mountain, found southwest of the town of Chewelah. This field site did not produce a coherently measurable section due to heavy vegetation cover, but was valuable for collection and field analysis of trace fossils. Most of Stevens County was explored for additional field localities, but this was deemed unproductive because of vegetation cover and lack of accessible roads.

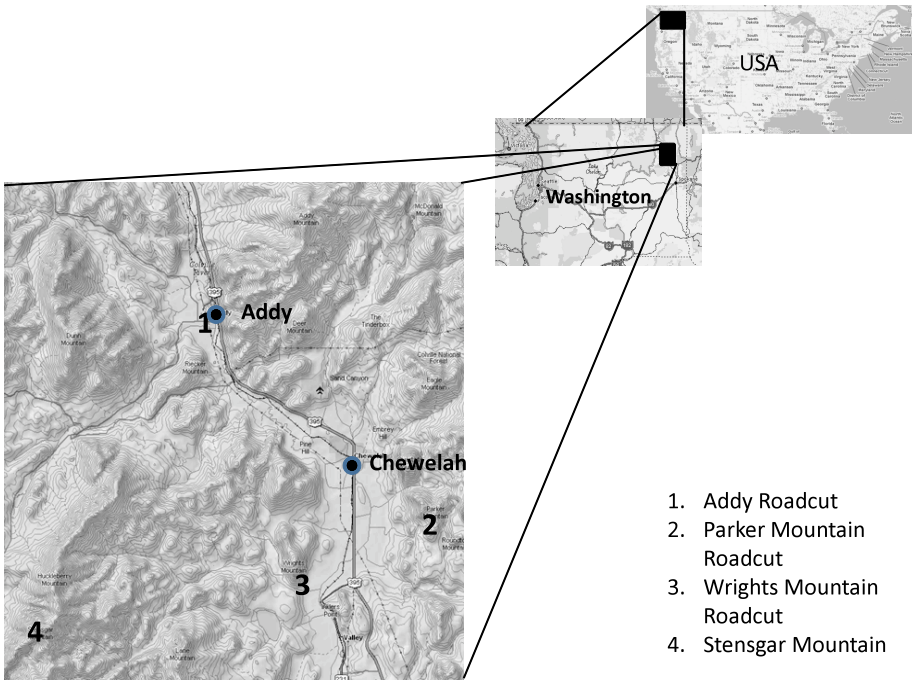

Figure 2.1. Field localities 1 through 4. Outcrops and collection sites of the Addy Quartzite in Stevens County, northeast Washington State, USA.

3.0 Sedimentology

3.1 Methods

Sedimentologic features of the Addy field sites were described and analyzed during two separate field seasons. Three road cuts (Addy Roadcut, Parker Mountain, and Wrights Mountain Roadcut) were the primary source of data as they provided the most well-preserved and continuous sections (Figure 2.1). Bed-by-bed stratigraphic sections were measured in these roadcuts wherever well-exposed outcrops allowed it. Facies were first identified in the field and later grouped into facies associations. Facies and facies associations were characterized based upon lithology, sedimentary structures, bed contacts, bed geometry, and ichnofauna. Sedimentary processes and sedimentary environments were evaluated after this information was compiled. Analysis was done by visual identification, measured using measuring tape and small rulers, use of grain size cards, and an abundance of pictures were taken with a Canon Rebel XR digital SLR camera for later reference and descriptive purposes.

3.2 Facies

A total of twelve sedimentary facies are recognized from the Addy Quartzite (Table 3.1). Sigmoidal-shaped, bioturbated and trough-cross stratified sandstone reflects high-energy, bed-load deposition of 3D-dunes with local, rare suspension fallout in a compound-dune field. Massive, planar cross stratified and planar laminated sandstone represents low- to high-energy bed-load and suspension fallout deposition related to the migration of 2D dunes in a compound-dune field. Ripple cross-laminated, planar-laminated, and wavy- and lenticular-bedded sandstone, as well as laminated siltstone reflect low- to moderate-energy conditions and suspension fallout and episodic bed-load deposition. These facies were deposited as small bedforms produced by wave reworking of compound-dune bottomsets and wave-reworked interdune areas. The normally graded sandstone represents deposits associated with transgressive lags.

Table 3.1.Sedimentary Facies of the Addy Quartzite

Facies	Lithology & Sedimentary Structures	Depositional Processes	Facies Association(s)	Sedimentary Environment
S_M Massive sandstone	Tabular beds, thin- to thick-bedded, well-sorted, fine- to coarse-grained. sandstone; structureless appearance.	Low to moderate energy; bed-load deposition	FA-2	Compound-dune field.
S_{SIG} Sigmoidal shaped, cross-stratified sandstone	Sigmoidal-shaped, cross-stratified moderately well- to well-sorted, fine- to coarse-grained sandstone. Sharp and erosive bases; sharp tops.	Moderate energy; bed-load deposition of 3D compound dunes during periods of strong current activity	FA-1	Compound-dune field.
S_B Bioturbated sandstone	Homogenized and cross-stratified, fine-grained sandstone with abundant *Skolithos linearis*.	Current-formed bedforms	FA-1	Compound-dune field.
S_R Ripple cross-laminated sandstone	Very thin- to thin-bedded, current rippled and cross-laminated, well-sorted, very fine- to fine-grained sandstone.	Low to moderate energy; bed-load deposition of small bedforms	FA- 3, 4	Dune-bottomsets and interdune areas.
S_P Planar cross-stratified sandstone	Tabular bodies, thin- to medium-bedded planar and low angle cross-Stratified well- to moderately sorted, fine- to medium-grained sandstone.	High energy; bed-load deposition	FA-2	Compound-dune field.
S_T Trough cross-stratified sandstone	Thin- to thick-bedded, trough cross-stratified, well- to moderately-sorted, fine- to coarse-grained sandstone.	High energy; bed-load deposition	FA-1	Compound-dune field.
S_L Planar laminated sandstone	Thin- to medium-bedded, planar laminated, well sorted, very fine- to medium-grained sandstone.	Low to moderate energy; bed-load deposition	FA-2,3,4	Compound-dune field, including bottomsets and interdune areas.
S_G Normally graded sandstone	Medium- to thick-bedded, normally graded sandstone; small- to medium-scale current rippled tops; sharp erosive bases.	Moderate to high energy; storm deposition and wave-reworked bedforms	FA-5	Transgressive lag deposits associated with dune bottomsets and interdunes.
Slt Laminated siltstone	Very thin- to thin-bedded, thinly laminated siltstone, local syneresis cracks.	Low energy; suspension fallout	FA- 4	Interdunes.
S_{WR} Rippled	Very thin- to thin-bedded, very fine grained, massive sandstone with small	Low energy; suspension fallout with sediment reworked by waves	FA- 3	Dune bottomsets.

sandstone	scale, rippled tops.			
H_1 Wavy-bedded sandstone	Intercalated thin- to medium-bedded, very fine- to fine-grained sandstone and thinly laminated siltstone. Local planar and ripple cross-lamination. Medium- to thick-bedded heterolithic packages.	Low energy; episodic sand deposition reflecting alternation of tidal currents, wave action and slack-water periods	FA- 3	Dune bottomsets.
H_2 Lenticular-bedded sandstone	Intercalated very thin- to thin-bedded very fine- to fine-grained sandstone and thin-bedded siltstone. Local planar and ripple cross-lamination. Thin- to medium-bedded heterolithic packages.	Low energy; bed-load deposition of small bedforms (wave and current ripples)	FA- 4	Interdunes.

3.3 Facies Associations

Five facies associations have been defined based on sedimentologic and depositional environment affinity (Table 3.2). All identified sedimentary facies were analyzed and grouped based on their implications for the depositional environment, and depositional conditions.

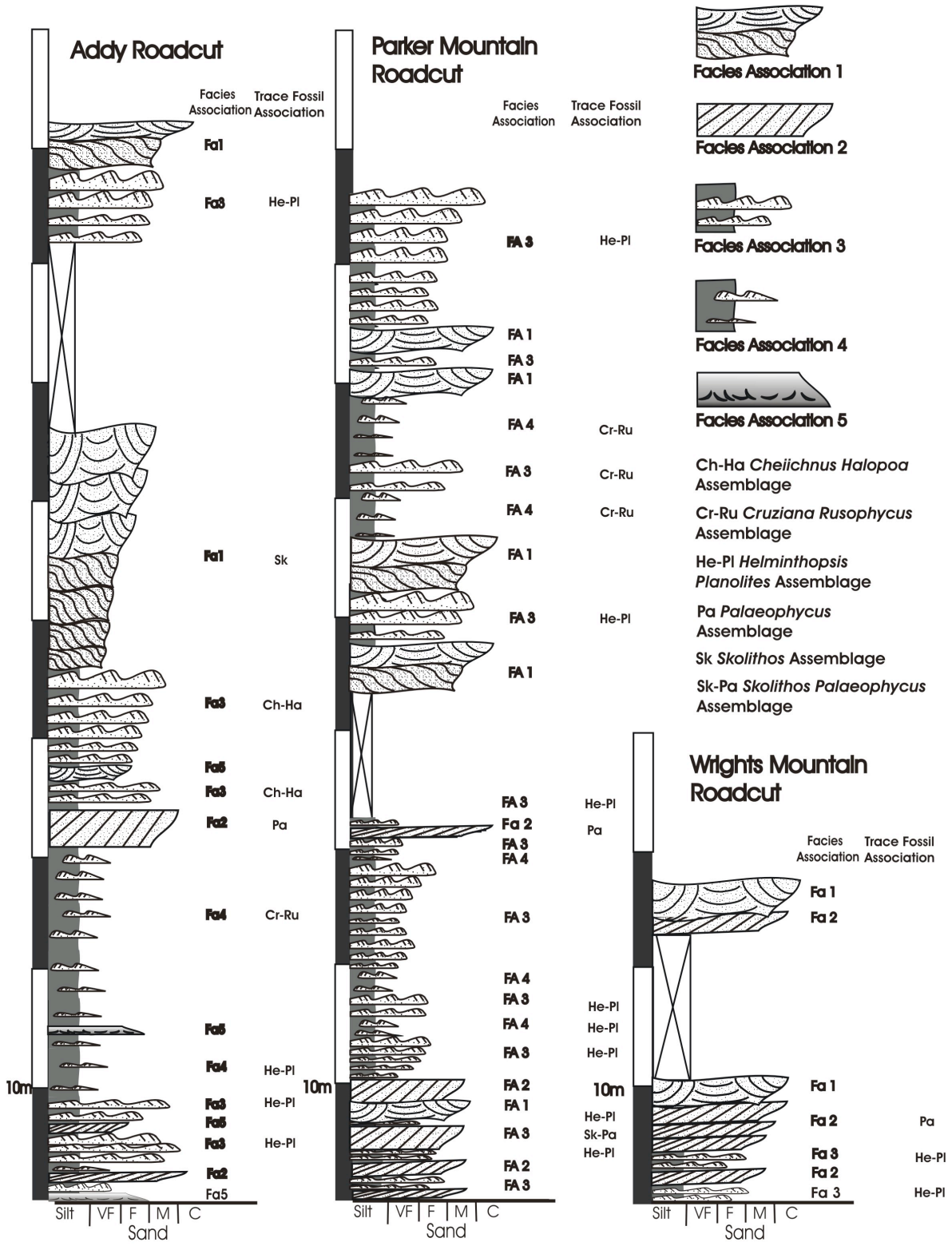

Figure 3.1.- Stratigraphic section of the upper unit of the Addy Quartzite at the Addy Roadcut, Parker Mountain Roadcut and Wrights Mountain Roadcut, northeast Washington State.

Facies Association 1 (Fig. 3.2A-C)

Facies association 1 includes the sigmoidal shaped ($\mathbf{S_{SIG}}$), bioturbated sandstone ($\mathbf{S_B}$) and trough cross-stratified sandstone ($\mathbf{S_T}$) facies. It comprises fine- to coarse-grained sandstone quartzite in sigmoidal beds. Sharp erosive bases and sharp tops are common. Small- to medium-scale, dune bedforms with wavelengths of 2.0-7.0 m and amplitudes of 15.0-30.0 cm are preserved on the tops of beds. Thin, intercalated, mud laminae are rare. Sandstone is well sorted and moderately well- to well-rounded. This facies occurs in packages of 0.15-19.0 m that coarsen and thicken upward. Bioturbation intensity is low to high (BI 0-5). Horizontal to sub-horizontal ichnofossils are represented by *Palaeophycus tubularis.* Vertical ichnofossils are represented by *Skolithos linearis.*
This facies association results from the deposition and migration of small to medium, 3D dunes in a compound-dune field (Dalrymple, 1992; Desjardins et al., in press).

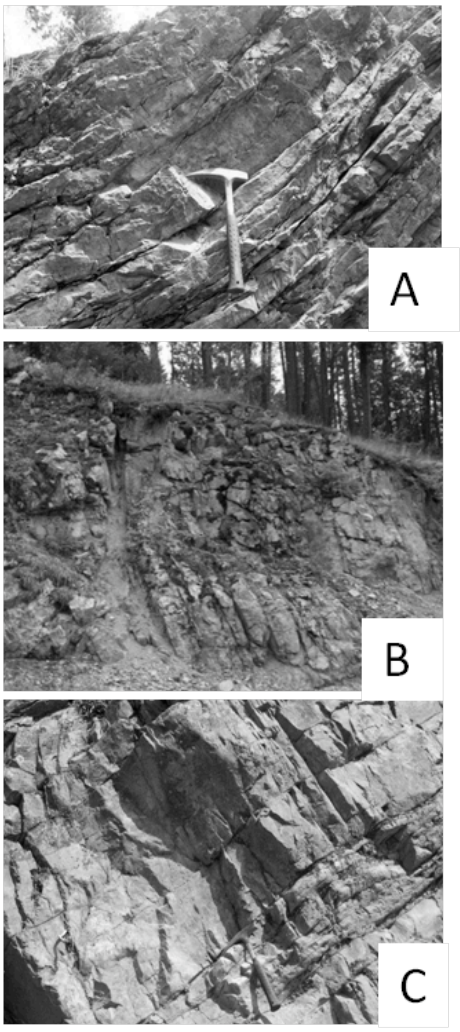

Figure 3.2. Facies Association 1. A) Sigmoidal bedded and Trough cross-stratified sandstones in the upper part of the Addy Roadcut. B) Sigmoidal bedded sandstones of Parker Mountain Roadcut. C) Sigmoidal bedded sandstones near mid-section of the Addy Roadcut.

Facies Association 2 (Fig.3.3A-C)

Facies association 2 includes the following: massive sandstone **(S_M)**, planar cross-stratified sandstone **(S_P)**, and planar laminated sandstone **(S_L)**. It is composed of tabular beds of coarse- to fine-grained quartzose sandstone that is moderately well sorted and subangular to moderately well rounded. FA-2 occurs in packages ranging from 0.44-4.10 m, which tend to coarsen and thicken upward.

Degree of bioturbation is low (BI 0-2). The predominant horizontal to sub-horizontal ichnofossils present are *Halopoa* isp. and *Palaeophycus tubularis*. Vertical ichnofossils are represented by *Skolithos linearis.*

This facies association arises from the deposition of small, 2D dunes in a compound-dune field (Dalrymple, 1992; Desjardins et al., in press).

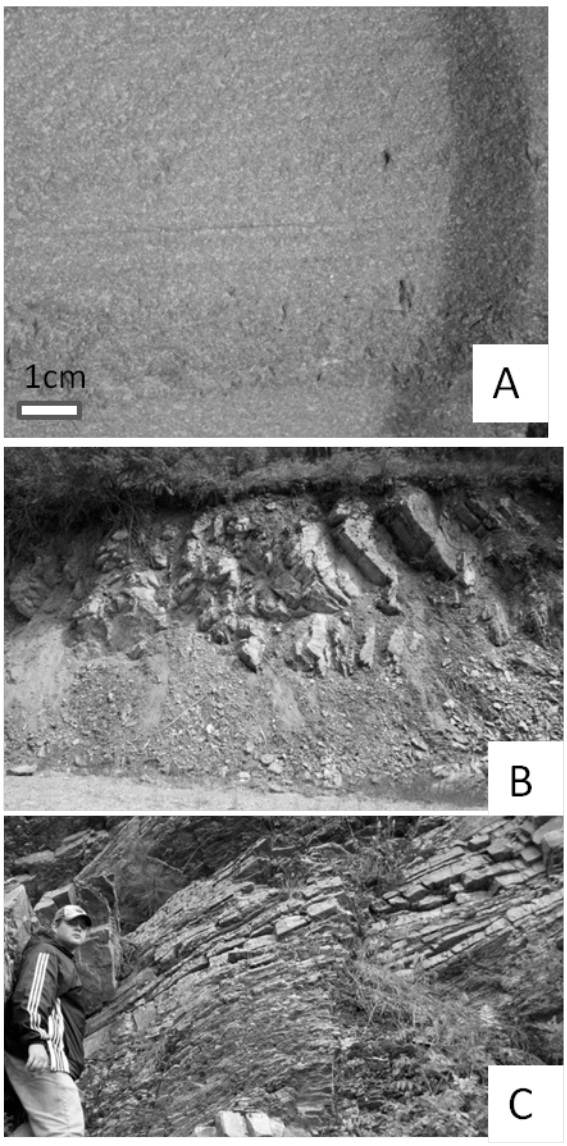

Figure 3.3- Facies Association 2. A) Planar laminated sandstone with *Palaeophycus tubularis*, full relief burrows. B) Medium bedded, tabular beds of Parker Mountain Roadcut. C) Thin to medium, tabular beds with planar stratification of Addy Roadcut.

Facies Association 3 (Fig. 3.4A-C)

Facies association 3 consists of intercalated wavy-bedded sandstone **(H_I)**, ripple cross-laminated sandstone **(S_R)**, planar-laminated sandstone (**S_L**), and rippled sandstone (**S_{WR}**) facies. Grain size is fine to medium. Sandstone intervals tend to be topped by asymmetric ripples, with a wavelength of 3.0-8.0 cm and an amplitude of 0.1-0.5 cm. Siltstone intervals are very thin to thinly bedded and are generally capped with symmetric ripples; wavelengths are 1.0-3.0 cm and amplitudes are 0.1-0.4 cm. Ripple-cross and parallel-laminated sandstone tends to be fine grained, while wavy sandstone ranges from fine to medium grained. Sandstone is well sorted and moderately well rounded. Sandstone intervals thicken, grain size increases, and sandstone beds tend to be more common while the siltstone intervals thin- and pinch-out and become less abundant up section. Packages are 0.77-9.24 m thick, and form coarsening-upward successions. Syneresis cracks are also common in the siltstone intervals of this facies. Bioturbation ranges from low to moderately high (BI 1-4). The predominant horizontal to sub-horizontal ichnofossils present in this facies are cf. *Asterosoma* isp., *Halopoa* isp., *Helminthopsis hieroglyphica, Palaeophycus tubularis, Planolites montanus, Rusophycus pectinatus* and *Rusophycus jenningsi.* Vertical ichnofossils are represented by, *Cheiichnus gothicus* and *Skolithos linearis*.

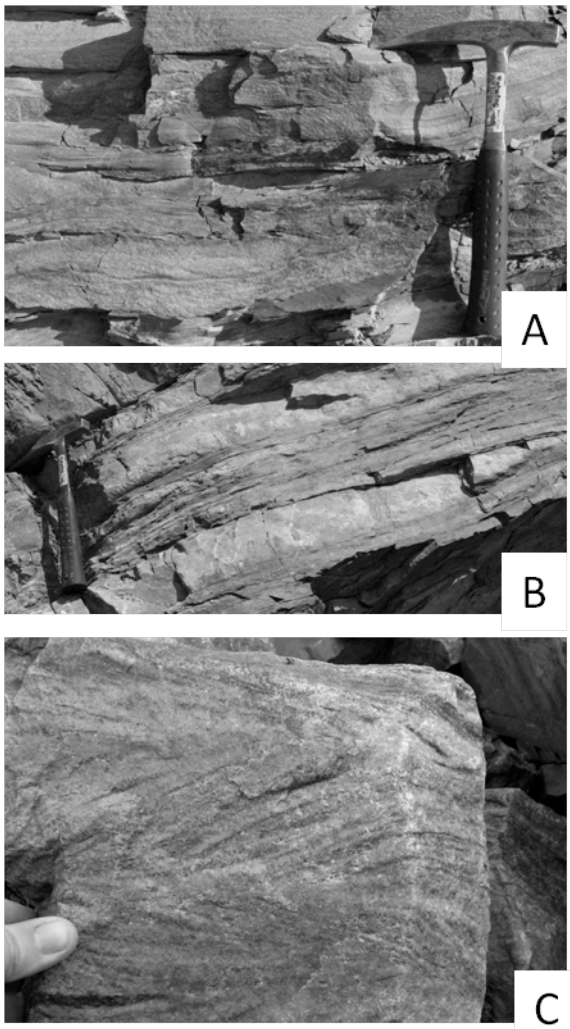

Figure 3.4- Facies Association 3. A) Amalgamated, very thin and thinly bedded, ripple cross- and planar laminated sandstone and wave rippled siltstone. B) Thin, wavy bedded sandstone interbedded with laminated siltstone. C) Ripple cross-laminated sandstones.

Deposition of this facies association occurred through traction and suspension fallout from low-energy, tide-generated currents in compound-dune bottomsets, with moderate wave reworking (Desjardins et al., in press).

Facies Association 4 (Fig.3.5A-C)

Facies association 4 is comprised of intercalated ripple cross-laminated sandstone **(S_R)**, planar laminated sandstone **(S_L)**, laminated siltstone **(Slt)**, and lenticular bedded sandstone **(H_2)** facies. Very fine- to fine-grained, well-sorted sandstone is dominant. Sandstone occurs in very thin beds to thin lenses. Siltstone intervals are thin to medium bedded. Finer-grained intervals are either rippled or thinly laminated. Siltstone bedforms in this association are relatively large symmetric ripples, with wavelengths of 4.0-15.0 cm and amplitudes of 0.6-0.9 cm, which are capped by smaller-scale asymmetrical ripples, with wavelengths of 1.0-3.0 cm and amplitudes of 0.2-0.4 cm. Sandstone is well sorted, with moderately well rounded to well rounded grains. Sandstone in this facies association tends to be much more friable than in the other facies. Siltstone interval thickness remains constant throughout each package, while sandstone beds vary in thickness and the degree of pinching and swelling throughout the package. Packages are 0.39-16.48 m, forming coarsening- and thickening-upward successions. Syneresis cracks are common in the siltstone intervals.

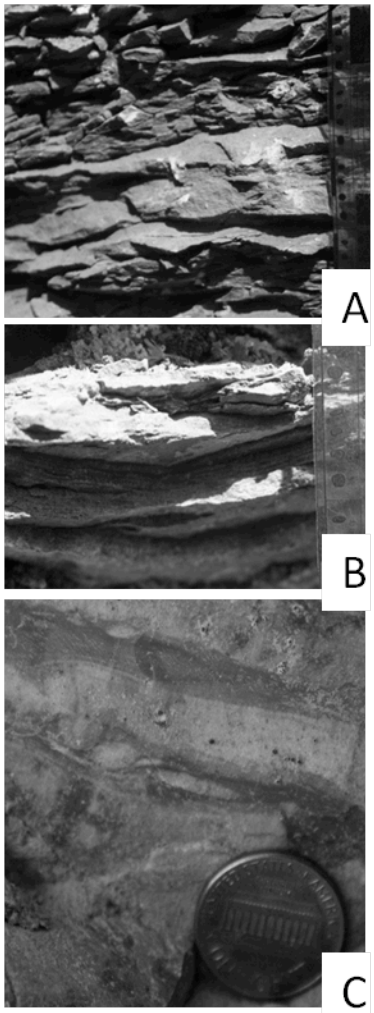

Figure 3.5- Facies Association 4. A) Wavy bedded sandstone and laminated siltstone. B) Thinly bedded, planar laminated sandstone. C) Intercalated wave rippled sadnstone and siltstone with full relief *Planolites montanus* burrows in siltstone.

Bioturbation is moderate to high (BI 3-5). The predominant horizontal to sub-horizontal ichnofossils present include cf. *Asterosoma* isp., *Cruziana pectinata, Helminthopsis hieroglyphica, Palaeophycus tubularis*, *Planolites montanus, Rusophycus pectinatus* and *Rusophycus jenningsi*. Vertical ichnofossils are represented by *Cheiichnus gothicus.*
Sparse body fossils of brachiopods as well as fragmentary trilobites and hylothids occur in this facies association.
Deposition took place through suspension fallout and episodic sand emplacement in a low-energy setting, via tide-generated currents and subsequent wave reworking in interdune areas developed between the compound-dunes (Desjardins et al., in press).

Facies Association 5 (Fig. 3.6A-B)

Facies association 5 consists of the normally graded sandstone ($\mathbf{S_G}$) facies. It is characterized by very fine- to medium-grained sandstone. Beds display slightly erosive bases with a basal shell lag. The tops of these beds are capped with small-scale symmetrical ripples, with a wavelength of 2.0-4.0 cm and an amplitude of 0.3-0.5 cm. The sandstone is dominated well sorted and well rounded quartz grains. Packages are 0.14-2.0 m, and form fining-upward successions.
Fragmentary shell fossils are found as a basal lag in this facies association. No trace fossils are present.
This facies association represents transgressive lag deposits and is found associated with wave-reworked compound bottomsets and interdune areas of the compound-dune field (Cattaneo and Steel, 2003; Desjardins et al., in press).

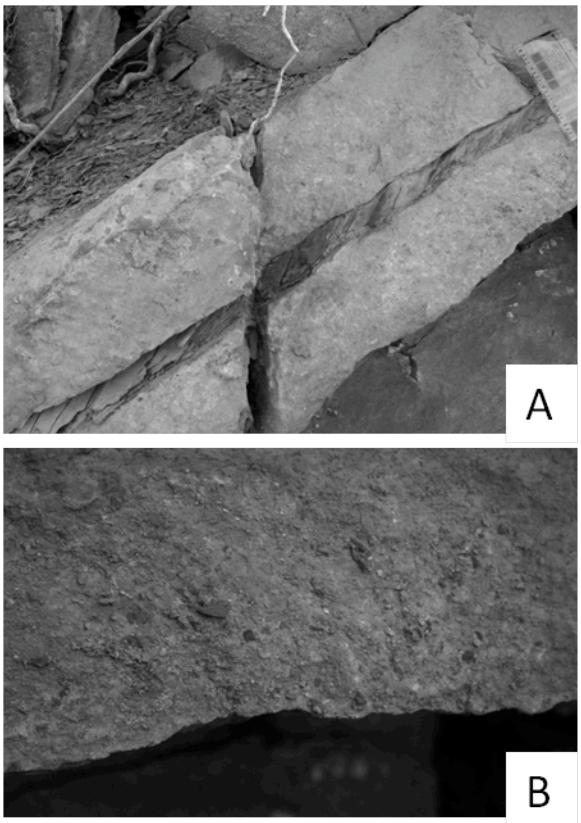

Figure 3.6- Facies Association 5. A) Normally graded transgressive lag deposits separated by laminated siltstone. B) Basal shell layer with fragmented trilobite fossils at the base of a transgressive lag.

Table 3.2. Facies Associations of the Addy Quartzite

Facies Association	Lithology	Sedimentary structures	Ichnofauna	Depositional Conditions and Sedimentary Processes	Sedimentary Environments
1. Laterally extensive quartzite beds with sigmoidal stratification	Thin- to thick-bedded, well sorted, upper fine- to lower coarse-grained sandstone with thin mud lamina.	Internally, sandstone beds display planar or trough cross-bedding. Sharp, undulating, erosive bases. Sharp tops.	*Palaeophycus tubularis,* and *Skolithos linearis.*	Tractive bed-load deposition. Migration of 3D dunes.	Compound-dune field core
2. Tabular quartzite with low-angle planar or parallel lamination.	Thin- to medium-bedded, upper fine- to lower coarse-grained sandstones.	Internally the beds display thin low-angle planar and parallel lamination or have a massive appearance . Sharp bases and sharp tops. Coarsening- and thickening-upward packages.	*Halopoa* isp., *Palaeophycus tubularis,* and *Skolithos linearis.*	Tractive bed-load, minor suspension fallout deposition. Migration of 2D dunes.	Compound-dune field margins and front
3. Wavy-bedded heterolithics	Thin- to medium-bedded, medium- to fine-grained sandstone, interbedded with very thin- to thin-bedded siltstone.	Ripple cross-laminated wavy bedded sandstone, with intermittent mudstone drapes. Interbedded with rippled siltstone. Syneresis cracks abundant. Coarsening-upward packages.	cf. *Asterosoma* isp., *Cheiichnus gothicus, Halopoa* isp., *Helminthopsis hieroglyphica, Palaeophycus tubularis, Planolites montanus, Rusophycus pectinatus, Rusophycus jenningsi* and *Skolithos linearis.*	Wave-reworked bedforms formed through the alternation of traction and suspension fallout deposition from low-energy, tide-generated currents.	Compound-dune field bottomsets.
4.Lenticular-bedded heterolithics	Thin- to medium-bedded siltstone interbedded with very thin to thin lenses of very fine- to fine-grained sandstone.	Laminated and tabular siltstone. Interbedded with ripple- and planar cross-laminated, lenticular bedded, sandstone. Sparse beds of thinly laminated siltstone.	cf. *Asterosoma* isp., *Cheiichnus gothicus, Cruziana pectinata, Helminthopsis hieroglyphica, Palaeophycus tubularis, Planolites montanus and Rusophycus pectinatus.*	Wave-reworked bedforms formed through suspension fallout and episodic sand deposition in a low-energy setting with tide-generated currents.	Interdune areas between compound dunes.
5. Normally graded quartzite	Normally graded, very fine- to fine-grained sandstone.	Basal shell lags along erosive bases. Sharp tops with rare wave ripples.	None	Tractive bedload high-energy currents.	Transgressive lag deposits.

4.0 Trace Fossils

4.1 Methodology

Trace-fossil analysis included field observations and more detailed lab study at the University of Saskatchewan. Well-preserved, sizable specimens were collected as hand samples and transported back to the lab for further analysis (i.e. polished cross-sections, photography), and detailed comparison with other researchers published material. Specimens were obtained and bagged with appropriate labels. Labels were recorded with the stratigraphic position, where samples were found *in situ*, and the date of collection. Detailed notes were made in field notebooks on any specimens that were non-transportable. Numerous pictures were taken in the field using a Canon Rebel XR Digital SLR camera to illustrate the recorded ichnotaxa. Laboratory photographs were taken using a Sony Alpha 200 digital camera, after specimens were blackened and coated with ammonium chloride.

4.2 Ichnotaxonomy

cf. *Asterosoma* isp.
Plate 5 C-D

Material: One specimen from the Burke Museum Addy Quartzite collection. No other specimens were observed in the field.

Description: Predominantly inclined, irregular, radiating burrow, with arms that taper distally away from the center, some forming a fusiform shape. Burrow arms are circular to oblong in cross section, and consist of concentric laminae of sand and silt packed around a central tube. Burrow fill is coarser than the host sediment, and tends to contain body-fossil fragments. Diameter of radial arms is 8.0-34.0 mm. Burrows are preserved as full relief.

Remarks: cf. *Asterosoma* isp. is identified by its internal structure of mud and sand and the radiating, concentrically filled arms (Pemberton et al., 2001; Seilacher, 2007). The Addy specimens are poorly preserved, and are only recognized as asterosomid in nature in cross section; the typical flower shape was not recorded here. Sediment manipulation within the burrow produced ornamented walls with longitudinal cracks and microfaults, resulting from pressure upon the walls by the host organism in an attempt to store waste (Seilacher, 2007). The Addy Quartzite specimens are differentiated from *Rosselia* isp. by the more horizontal nature of multiple components forming radial structure. The precise 3D morphology of these structures is difficult to reconstruct preventing a precise taxonomic assignment. The burrow fill suggests an

active infill, and the body fossil fragments of unknown taxonomic affiliation lend weight to the belief that waste is used to shore up walls.

Occurrence: cf. *Asterosoma* isp. is rare within the Addy Quartzite. It occurs in sand-dominated heterolithic intervals, which represent compound-dune bottomsets. These deposits also contain *Cheiichnus gothicus, Palaeophycus tubularis, Planolites montanus* and *Skolithos linearis.*

Cheiichnus gothicus Jensen and Bergström, 2000
Plate 2 C-D

Material: Three specimens in two slabs. Only one specimen is complete and well preserved. The other specimens are broken and are tentatively placed within this ichnospecies. Six additional, incomplete specimens were examined in the field. Recovered from Addy Roadcut and Parker Mountain Roadcut.

Description: Plug-shaped trace fossil, with slightly sloping side walls and a flat bottom which displays neither an apical depression nor protuberance. Walls display radiating longitudinal ridges and furrows. The ridges appear nearly parallel to one another, and terminate towards the central burrow apex. Clear well-defined scratch marks are the only burrow ornamentation. Burrow fill is fine-grained sandstone. Depth is 9.75 mm, width is 18.3 mm, and height/diameter ratio is 1:1.87. *Cheiichnus gothicus* is typically preserved as full-relief structures within siltstone intervals.

Remarks: *Cheiichnus gothicus* is a recently described trace fossil that is similar to other plug-shaped burrows, such as *Bergaeuria* and *Conostichus* (Jensen and Bergström, 2000). However, the lack of an apical disc, no evidence of transverse constrictions, and the presence of clearly defined scratch marks along the walls of the Addy specimens is characteristic of *C. gothicus*. There is considerable variation in dimension amongst the type specimens from the Mickwitzia sandstone in Sweden. Specimens from the Addy Quartzite are very small compared to those found in similar units around the globe and may represent juvenile burrow forms. It has been suggested that there may be a gradation from *Rusophycus jenningsi* to *C. gothicus* in the Mickwitzia Sandstone, Sweden (Jensen and Bergström, 2000) and the Gog Group in western Canada (Fenton and Fenton, 1937). *Cheiichnus gothicus* is interpreted as resulting from rotational behaviour in arthropods, and is likely produced by olenellid trilobites (Jensen and Bergström, 2000).

Occurrence: *Cheiichnus gothicus* is quite rare within the Addy Quartzite. It occurs within the heterolithic facies, representing compound-dune bottomsets and interdune areas. It is typically associated with cf. *Asterosoma* isp., *Halopoa* isp*., Planolites montanus,* and *Skolithos linearis.*

Cruziana pectinata Seilacher, 1994
Plate 2 A

Material: One specimen in one slab (ARC149). Recovered from Addy Roadcut.

Description: Relatively large, straight, bilobed structure. The anterior margin shows a rounded ridge. Lobes are well developed, with a shallow, very wide U-shaped median furrow in between. The left lobe margin is near vertical with a sharp ridge alternately present, while the right lobe margin tapers at a shallow angle into the surrounding sediment. Lobes are composed of retroverse endopodal scratch marks, which are faint, shallow and have rounded profiles. Scratch marks occur in bundles of 9-12. Bundles appear as a near transverse, coarse structure constrained toward the midline. Scratches on these coarse bundles come together along the median furrow at an angle of 85-115°; this angle widens towards the anterior portion of the burrow. Exopodal brushings are also present on the outer margins of the lobes. These brushings are wide angled, introvert, and run longitudinal to the median axis. Each exopodal scratch is 0.4-0.6 mm thick, and bundles are 5.0-6.0 mm apart. Trace-fossil width is 68 mm, depth is up to 12 mm, and partial length is 120 mm. This ichnotaxon is preserved as a convex hyporelief.

Remarks: The specimen described above is the only example of a cruzianiform trace fossil recovered from the Addy Quartzite during the present investigation. The anterior marginal ridge is attributable to a cephalic impression which indicates a prosocline burrowing method (Fenton and Fenton, 1937; Seilacher, 1994). The broad U-shaped median furrow contains large, coarse, bundled and nearly transverse endopodal scratches. The appearance of prominent introvert exopodal brushings and fine brushings associated with the type of aforementioned endopodal scratches, make this specimen attributable to *Cruziana pectinata*.

Occurrence: *Cruziana pectinata* is very rare within the Addy Quartzite. It occurs at the base of a medium-grained sandstone bed within a lenticular bedded heterolithic interval, representing wave-reworked interdune areas of the compound-dune field. This ichnotaxon is associated with *Planolites montanus, Palaeophycus tubularis,* and cf. *Asterosoma* isp.

Dactyloidites asteroides Fitch 1850
Plate 5 A-B

Material: One specimen in one slab from the Burke Museum Addy Quartzite collection. No other specimens were observed in the field.

Description: Rosette-like, horizontal structure, having 4 to 5 rays or probes radiating from a central vertical, depressed structure. Ghost walls are present; no ornamentation is associated with the wall structure. Protrusive radial spreite, although obscure, is observed on the rays of the structure. This structure is preserved as negative epichnial structures.

Remarks: *Dactyloidites* has recently being revised, and the ichnogenera *Brooksella* Walcott, 1896 and *Haentzschelinia* Vialov, 1964 as its junior synonyms (Uchman and Pervesler, 2007). Other ichnogenera are believed to be synonymous with this ichnogenus, but a comprehensive review of the taxonomy of these traces is required (Seilacher, 2007; Uchman and Pervesler, 2007). The Addy Quartzite specimen is well preserved in negative epirelief, although the relief of the petals is lacking making establishment of the number of petals difficult. Protrusive radial spreite is diagnostic of this trace and allows for differentiation between cf. *Asterosoma* isp., which is another radial trace fossil in the Addy Quartzite.

Occurrence: This ichnospecies is very rare within the Addy Quartzite. No specimens were found *in situ*, and as such its precise stratigraphic context is uncertain. However, the specimen is found associated with heterolithic facies. This trace fossil is associated with *Planolites montanus*.

Halopoa isp.
Plate 4 D-F

Material: Seven specimens in seven slabs; one additional specimen was observed in the field. Recovered from Addy Roadcut and Wrights Mountain Roadcut.

Description: Long, straight and tube-like burrows. Burrow walls invariably display a faint thread-like, impressed pattern on the walls. Primary branching is common and burrows also cross and interpenetrate. Burrows are infilled with sediment similar to the host rock. Width is 16.0-19.0 mm. Partial length is more than 80.0 mm. These burrows are preserved as positive epireliefs.

Remarks: The large size and long, longitudinal scratch marks parallel to the burrow boundary, create a sort of thread-like effect, which follows the descriptions of this ichnogenus by Uchman (1998) and Seilacher (2007). The tracemaker is believed to be a worm-like animal bearing no hard outer cuticle, thus allowing the organism to expand its body to create the compressionary stress cracks reflected by the thread-like effect (Seilacher, 2007). All Addy Quartzite specimens are straight and tube-like, and are found at the top of the sand/mud interface. Many specimens overcross such that they may appear superimposed upon one another.

Occurrence: *Halopoa* isp. is rare in terms of preserved number of specimens within the Addy Quartzite. However, it is found in most of the facies defined within the Addy Quartzite, which may suggest preservation potential was relatively low. It is associated with *Cheiichnus gothicus, Helminthopsis hieroglyphica, Palaeophycus tubularis,* and *Planolites montanus* in facies association 3, representing wave-reworked compound-dune bottomsets. *Halopoa* isp. is associated with *Palaeophycus tubularis*, *Planolites montanus,* and *Skolithos linearis* in facies association 2, representing migration of 2D dunes in the compound-dune field.

Helminthopsis hieroglyphica Wetzel and Bromley, 1996
Plate 3 A-B

Material: Ten specimens in six slabs; many more specimens were observed in the field. Recovered from Addy Roadcut and Parker Mountain Roadcut.

Description: Meandering to loosely winding, unlined, unornamented trails. Trails may be circular to elliptical in cross section. Most of them show alternation between straight segments and meandering segments with low-amplitude curves. Specimens never self cross, but overlap among specimens is common. The burrow fill is the same as the host rock. Width is 1.5-3.4 mm. Burrows are preserved as positive hyporeliefs.

Remarks: *Helminthopsis* has been revised by Han and Pickerill (1995), and Wetzel and Bromley (1996). The typical defining characteristic of *H. hieroglyphica* is the presence of alternate segments of straight and irregular low-amplitude meanders (Han and Pickerill, 1995; Wetzel and Bromley, 1996). However, some of the specimens collected from the Addy Quartzite do not have enough of the trace preserved to make a definitive designation as to the true path of the meander. Some of these small pascichnial traces show small levee-like accumulations of sediment. Some specimens appear to emulate *H. sigmoideus* of Wang 1989, but due to the lack of type material this ichnospecies is a *nomen dubium*. As such, the traces in question are included in *H. hieroglyphica*. This ichnotaxon is interpreted as grazing trails (Pascichnia) of worm-like organisms, such as nematodes (Wetzel and Bromley, 1996).

Occurrence: *Helminthopsis hieroglyphica* is relatively common. It is found in the siltstone and sandstone of the heterolithic intervals, representing wave-reworked compound-dune bottomsets and interdune areas of the compound-dune field. It is associated with *Cheiichnus gothicus*, *Cruziana pectinata*, *Halopoa* isp., *Palaeophycus tubularis, Planolites montanus,* and *Rusophycus pectinatus.*

Palaeophycus tubularis Hall, 1847

Plate 3 E-F

Material: Eighty five specimens in twenty eight samples; many more specimens were observed in the field. Recovered from Addy Roadcut, Parker Mountain Roadcut, Wrights Mountain Roadcut and Stensgar Mountain.

Description: Cylindrical, sinuous burrows that exhibit smooth lined walls. Burrow infill is the same as the host rock. Width is 2.9-12.1 mm. Burrows are preserved at the base of sandstone beds as convex hyporeliefs or found within fine-grained intervals as full relief burrows.

Remarks: *Palaeophycus tubularis* is distinguished from other *Palaeophycus* ichnospecies by the presence of a thin, dust film type wall and lack of ornamentation (Pemberton and Frey, 1982). Wall collapse is common in Addy specimens. Specimens of the Addy Quartzite have a burrow infill similar to the host rock, distinguishing it from *Planolites montanus*, also found in the Addy Quartzite. Eleven valid ichnospecies of *Palaeophycus* are currently recognized: *P. tubularis* Hall 1847, *P. striatus* Hall 1852, *P. heberti* deSaporta 1872, *P. sulcatus* Miller and Dyer 1878, *P. alternatus* Pemberton and Frey 1982, *P. ferrovittatus* Hofmann 1983, *P. subornatus* Ghare and Kulkarny 1986, and *P. crenulatus* Buckmann 1995. *Palaeophycus tubularis* is interpreted as the dwelling structures (domichnia) of polychaete-like predators or suspension feeders (Pemberton and Frey, 1982).

Occurrence: *Palaeophycus tubularis* is abundant in the Addy Quartzite ichnofauna. It is found in facies associations 1, 2, 3 and 4 within the unit. In the sandstone units, *P.tubularis* is associated with *Halopoa* isp.*, Planolites montanus* and *Skolithos linearis.* In the heterolithic units *P. tubularis* is associated with cf. *Asterosoma* isp., *Halopoa* isp.*, Helminthopsis hieroglyphica, Planolites montanus, Rusophycus pectinatus, Rusophycus jenningsi* and *Skolithos linearis.*

Planolites montanus Nicholson, 1873
Plate 3 C-D

Material: Sixty specimens in thirty seven slabs; numerous specimens also studied in the field. Recovered from Addy Roadcut, Parker Mountain Roadcut, Wrights Mountain Roadcut and Stensgar Mountain.

Description: Straight to slightly curved, horizontal to inclined cylindrical structures. The specimens from the Addy Quartzite are generally poorly preserved. No branching has been observed, but individual structures may overcross one another. The structure infill is different from the host rock. Width is 4.2-8.4 mm. These structures occur primarily as full reliefs which

tend to cross through sandstone and siltstone intervals, but are also found as convex hyporeliefs on the soles of siltstone beds.

Remarks: The Addy Quartzite specimens of *P. montanus* conform to the description given by Pemberton and Frey (1982). Specimens have an infill different from the host rock which distinguishes them from *Palaeophycus tubularis*, also commonly found in association. The grain size of the infill is generally coarser and different in colour from the surrounding host rock (see Pemberton and Frey, 1982). *Planolites montanus* differs from other species of *Planolites* by the contorted burrow course. Five *Planolites* ichnospecies are at present recognized as valid: *P. beverlyensis* Billings 1862, *P. annulatus* Walcott 1890, *P. montanus* Richter 1937, *P .terranovae* Fillion and Pickerill 1990, and *P. constriannulatus* Stanley and Pickerill 1994. *Planolites montanus* is believed to be the feeding structure (Fodinichnia) of a vermiform organism, most likely a deposit-feeding polychaete (Pemberton and Frey, 1982), which actively infills the structure as the animal passes the sediment through its gut.

Occurrence: *Planolites montanus* is abundant in the Addy Quartzite, occurring in the heterolithic intervals, which represent wave-reworked compound dune-bottomsets and interdune areas of the compound-dune field. This ichnospecies is most abundant in interdune areas of the compound-dune field. In sandy beds within the heterolithic intervals, *P .montanus* is associated with cf. *Asterosoma* isp*., Cheiichnus gothicus, Cruziana pectinata, Halopoa* isp*., Helminthopsis hieroglyphica, Palaeophycus tubularis, Rusophycus jenningsi, Rusophycus pectinatus,* and *Skolithos linearis*. In silty beds within the heterolithic facies, *P. montanus* is associated solely with *Helminthopsis hieroglyphica*.

Rusophycus jenningsi Fenton and Fenton, 1937
Plate 2 B

Material: One specimen on one slab. Recovered from Addy Roadcut.

Description: Large, elongate, bilobed structure. Width is slightly less than length. Lobes are well developed, and have near vertical walls. Endopodal scratch marks along the vertical sides are widely spaced apart. Shallow to moderately deep endopodal scratches are present on the lobes, and occur in bundles of at least 6 claw marks. Endopodal scratches are rounded to slightly angular in profile. The scratches meet at the median axis of the burrow; the angle of scratch intersection tapers from 65º in the anterior to 85º in the posterior section of the burrow. Individual endopodal scratches are 0.6-0.8 mm thick on the lobe base, and widen to 1-1.2 mm on the sides of the lobes. They are spaced 1 mm apart on the lobe base, and 2 mm apart on the sides of the lobes. Length is 88 mm, width is 66 mm, and depth is 32 mm. The burrow is a positive hyporelief.

Remarks: The specimen recovered is moderately well preserved and, although not found *in situ*, it is in sandstone layers included in heterolithic intervals of facies association 3. Although most scratch marks are well preserved, the lobes are damaged in areas making definite characteristics of this ichnospecies obscure. A precise number of claws per bundle is not easily recognized; however, it is remarkably similar to specimens of *Rusophycus jenningsi* found in southeastern and east central British Columbia. *Rusophycus navicellus* is suggested to be a synonym of *R.jenningsi* (Seilacher, 1970).

Occurrence: *Rusophycus jenningsi* is very rare in the Addy Quartzite. It is present on the sole of a thin layer of fine-grained sandstone in facies association 3, representing wave-reworked compound-dune bottom sets. It is associated with *Palaeophycus tubularis.*

Rusophycus pectinatus Seilacher 1994
Plate 1 A-D

Material: Two specimens, part and counter part (ARC9-pieces 1,2,3,4). Recovered from Addy Roadcut.

Diagnosis: Bilobate burrows, which display prominent, multiple exopodal scratches. Endopodal scratches are also prominent, particularly near the median furrow, which meet at an obtuse to transverse angle.

Description: Medium to large, elongate, bilobed structure. Lobes are moderate to poorly developed, and diverge towards the posterior part of the burrow giving the burrow a slight, heart-like shape. The lobes are separated by a very wide V-shaped median furrow. Lobes are composed of large endopodal scratches which meet along the median furrow at a nearly transverse angle. Each endopodal scratch bundle is 4.5-5.2 mm wide. Introvert, exopodal brushings are well preserved. The brushings run longitudinally down the lateral burrow margins. Both exopodal and endopodal markings are rounded in profile. Width is 52-76 mm, length is 47-91 mm, and depth is 34-39 mm. These specimens are preserved as positive hyporeliefs.

Remarks: The Addy Quartzite specimens display the characteristic scratch pattern of the ichnotaxon referred to as *Cruziana pectinata* by Seilacher (1994). However, these two Addy specimens are rusophyciform in nature, and relatively shallow. As *Cruziana* and *Rusophycus* are here considered, distinct ichnogenera, a new ichnospecies is erected for the rusophycid form. The typical introverted exopodal brushings (Seilacher, 1994), which are well preserved in one of the Addy specimens, take on a prominent role in the diagnosis of this ichnospecies. These brushings show an interesting alternative to the typical behavioural role of the exopodites as a respiratory

structure, becoming more clearly involved in locomotion, sediment processing, and excavation activities. This is consistent with the original diagnosis of *C. pectinata* (Seilacher, 1994). The best-preserved specimen of this ichnospecies (ARC9-piece4) is loaded on the right side which obscures the fine detail of the scratches on the left lobe; however, the right lobe is well preserved.

Occurrence: *Rusophycus pectinatus* is very rare within the Addy Quartzite. It is found in the within the sand-dominated heterolithic facies, representing wave-reworked compound-dune bottomsets. They are found on one slab containing both part and counterpart of two separate specimens. It is associated with *Planolites montanus* and *Palaeophycus tubularis*.

Skolithos linearis Halderman, 1840
Plate 4 A-C

Material: Sixty seven specimens in one slab; many more specimens studied in the field. Recovered from Addy Roadcut, Parker Mountain Roadcut, Wrights Mountain Roadcut and Stensgar Mountain.

Description: Straight, vertical, unbranched, cylindrical burrows. Burrow fill is massive and similar to the host rock. The infill of the structures abuts directly to the surrounding sediment, with no visible lining. Width is 3.1-9.2 mm. Minimum length recorded is 35 mm and maximum length recorded is 100 mm, although this is obscured by bed amalgamation and lack of exposure. Burrows are preserved as full reliefs.

Remarks: This ichnotaxon is generally recognized by being straight in nature and vertical in orientation (Alpert, 1974; Fillion and Pickerill, 1990). This ichnospecies forms dense monospecific associations, commonly referred to as pipe rock. There are seven *Skolithos* ichnospecies currently accepted: *S. linearis* Halderman 1840, *S. verticalis* Hall 1843, *S. serratus* Salter 1864, *S. magnus* Howell 1944, *S. ingens* Howell 1945, *S. annulatus* Howell 1957, *S. bulbus* Alpert 1975, and *S. gyratus* Hofmann 1979. *Skolithos* is interpreted as a dwelling structure produced by polychaetes and phoronids, among other animals (Alpert, 1974; Schlirf and Uchman, 2005).

Occurrence: *Skolithos linearis* is abundant within the Addy Quartzite. It occurs predominantly as monospecific suites in fine-grained sandstone (facies associations 1, 2 and 3). Four pipe rock units have been identified within sigmoidal-bedded sandstone of the Addy roadcut section, representing 3D dunes of the compound-dune field. It is also present in deposits recording 2D dunes also developed in the compound-dune field. , where it is associated with *Palaeophycus tubularis* and *Halopoa* isp. In the facies representing wave-reworked compound-dune bottomsets

and interdune areas, it is associated with cf. *Asterosoma* isp, *Cheiichnus gothicus, Halopoa* isp., *Helminthopsis heiroglyphica, Palaeophycus tubularis, Planolites montanus, Rusophycus jenningsi,* and *Rusophycus pectinatus*.

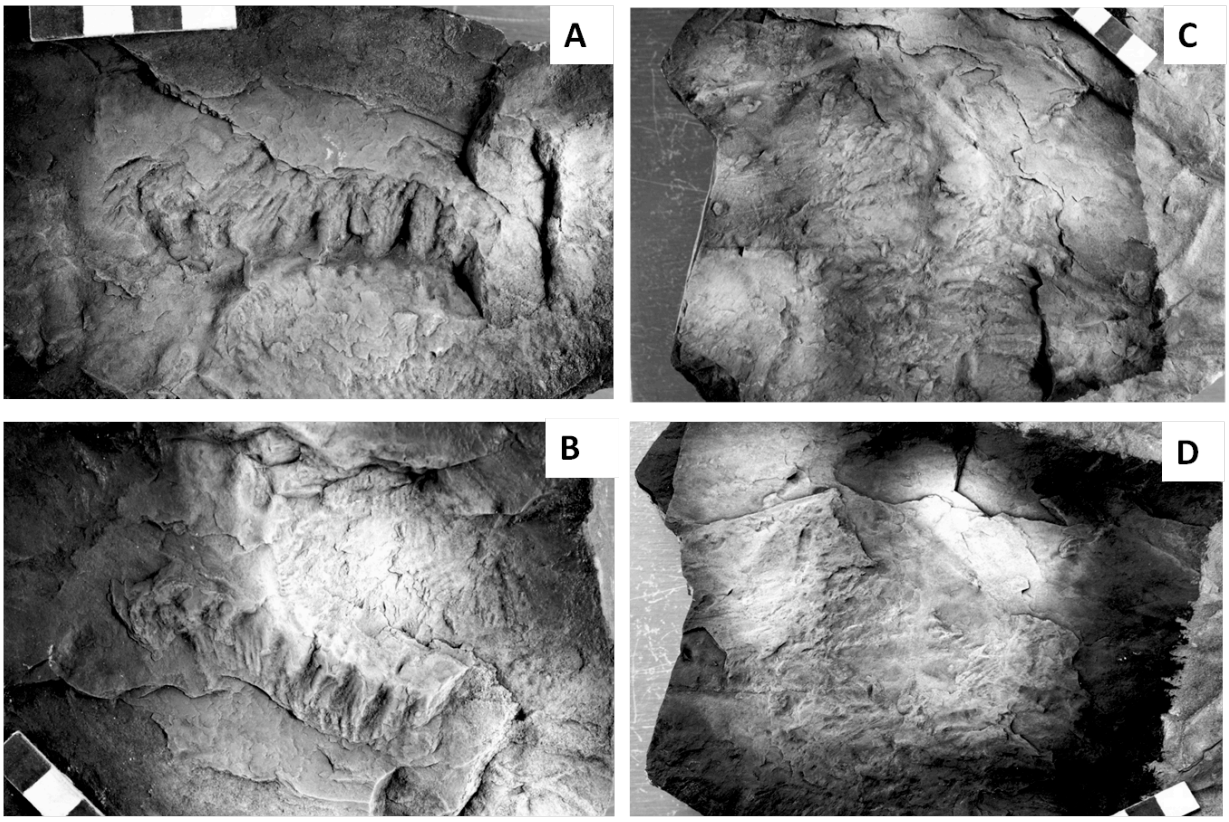

Plate 1- *Rusophycus pectinatus* from the Addy Quartzite. (A,B) Part and counterpart, respectively, (C, D) Part and counterpart, respectively. Both specimens were found on one slab, coming from FA3 at the Addy roadcut. Note poor preservation due to bed amalgamation, as well as loading on the specimen in A.

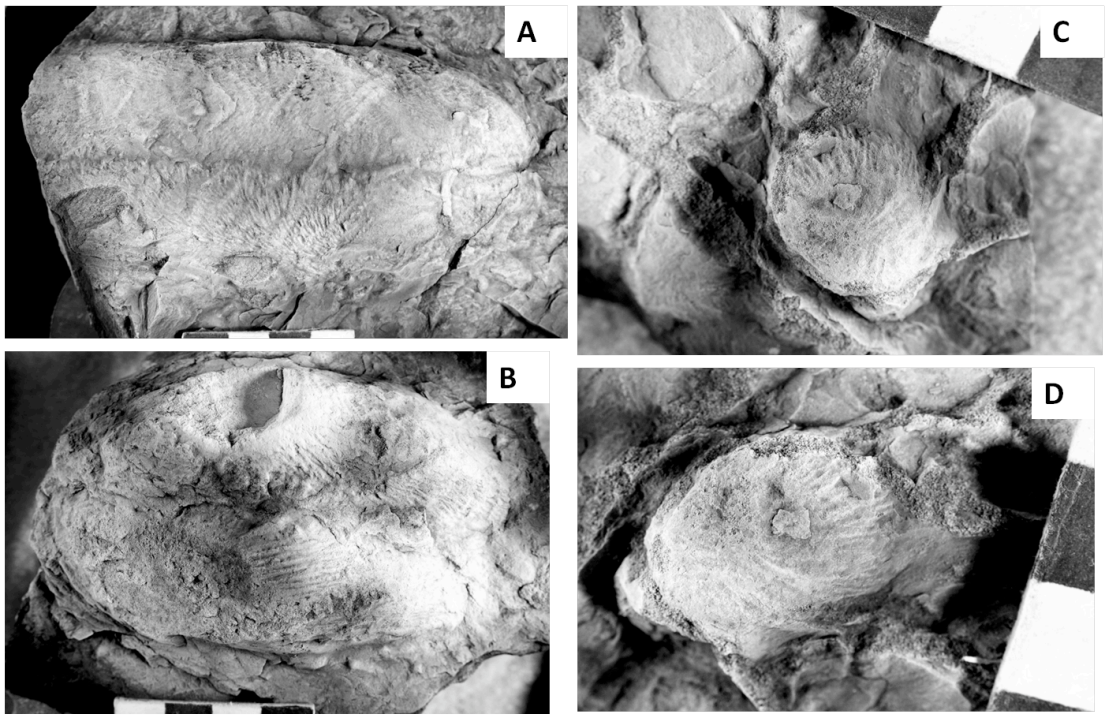

Plate 2- A) *Cruziana pectinata* preserved in FA4. B) *Rusophycus jenningsi* preserved in FA3. C, D) *Cheiichnus gothicus* preserved in FA3. Note the absence of any apical structure and the clear radiating scratch marks.

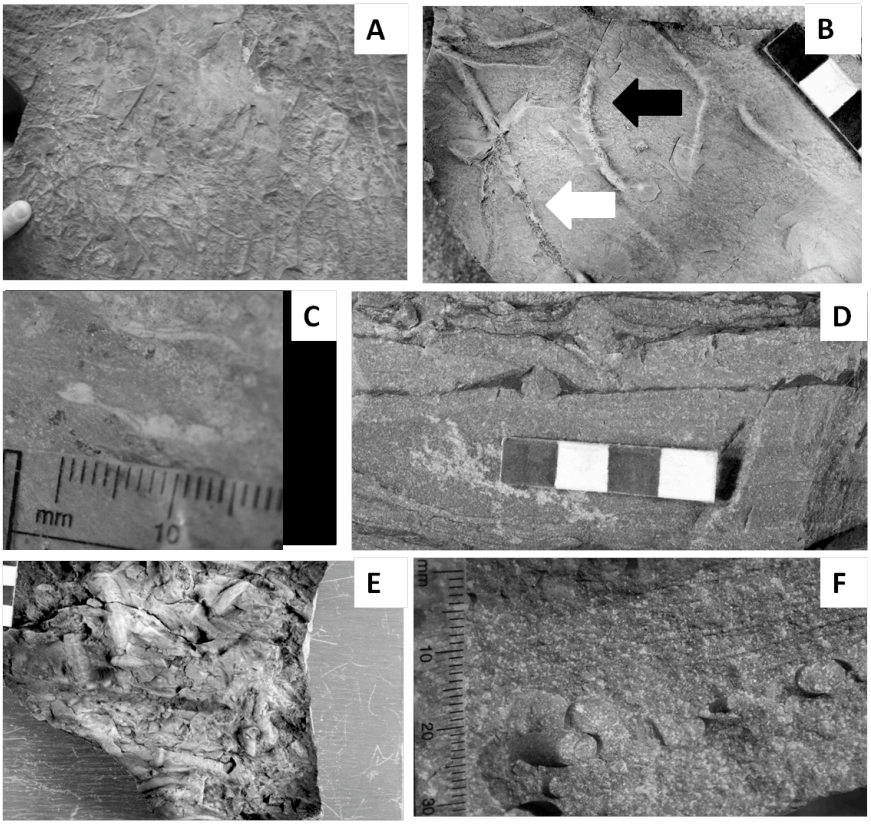

Plate 3- A) Abundant *Helminthopsis hieroglyphica* B) *Helminthopsis hieroglyphica* (Black Arrow) and *Planolites montanus* (White Arrow) in FA4. C) *Planolites montanus* in mudstone of FA4. D) *Planolites montanus* preserved in siltstone partings between ripple cross-laminated sandstone. E) Dense *Palaeophycus tubularis* found on sandstone soles in FA1. F) Full relief burrows of *Palaeophycus tubularis* preserved in planar laminated sandstones of FA2.

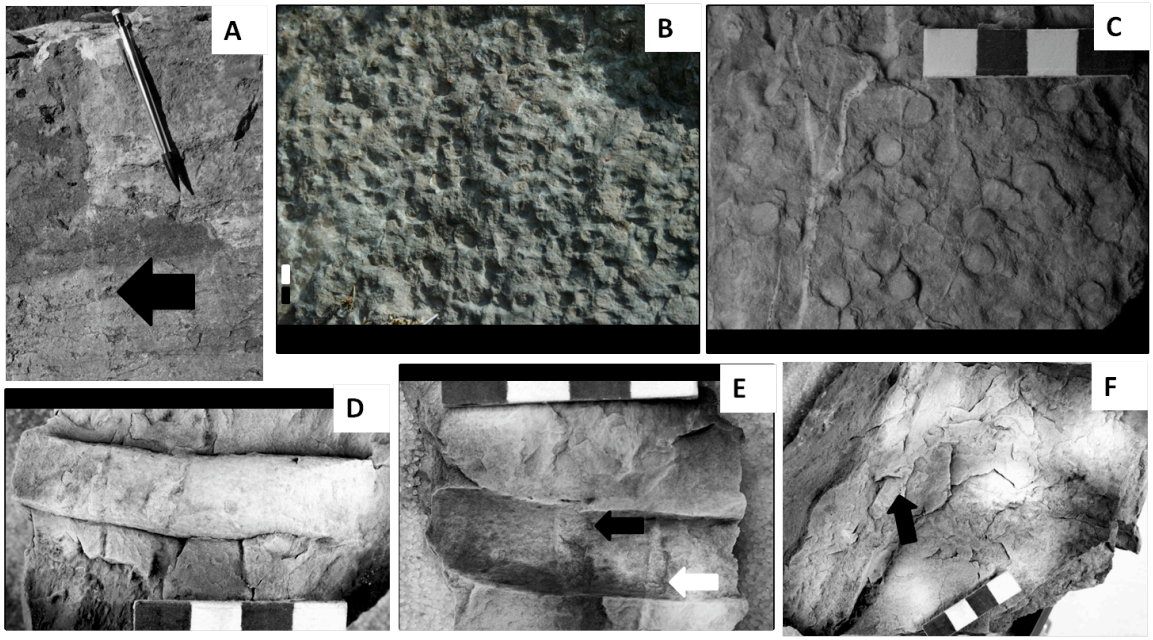

Plate 4- A) *Skolithos linearis* in cross sectional view (Black Arrow) preserved in FA2. B) Medium to large sized *Skolithos linearis* in dense monospecific pavement in FA1. C)Small sized, *Skolithos linearis* preserved in FA1. D, E) Part and counterpart, respectively, of a well preserved *Halopoa* isp., preserved in FA3; Note overcrossing *Planolites montanus* (White Arrow) and *Palaeophycus tubularis* (Black Arrow) in E. F) Poorly preserved *Halopoa* isp., showing branching (Black Arrow-branch node)

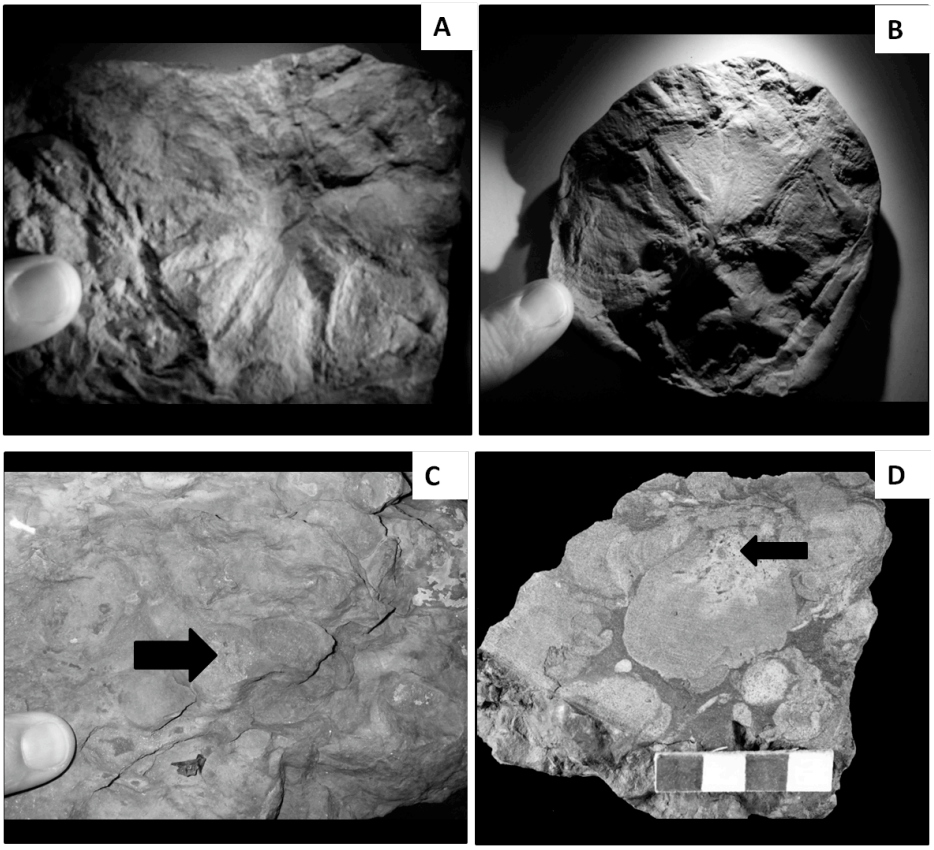

Plate 5- A) Base of bedding plane, view of *Dactyloidites asteroides*. B) Mold of bedding plane view of *Dactyloidites asteroides*. C) Bedding plane view of cf. *Asterosoma* isp., obliquely oriented burrow lobes with sand infill (Black Arrow). D) Internal structure of cf. *Asterosoma* isp., coarse infill with mud clasts surround a central mud-filled burrow (Black Arrow).

4.3 Trace Fossil Assemblages

Helminthopsis-Planolites Assemblage

This assemblage is found on the soles of laminated siltstone (**Slt**) and wave-rippled sandstone (**S_{WR}**) of facies associations 3 and 4. Trace-fossil density and diversity is low. The most common ichnofossil in this assemblage is *Planolites montanus*, while *Helminthopsis hieroglyphica* is rare. The resident benthic fauna was composed of small deposit- and detritus-feeding worm-like animals, such as nematodes and polychaetes. Integration of sedimentologic and ichnologic information suggests poor to moderately good oxygen conditions, normal salinity, and an abundant detrital food supply in the sediment accumulated in a low-energy environment. The facies associations hosting this assemblage are indicative of suspension fallout of silt particles, and some beds reflect deposition and subsequent reworking by tidal currents and oscillatory wave action. Microbial mat structures, wrinkle marks and syneresis cracks are locally present. The microbial mat structures and wrinkle marks are never directly associated with the trace fossils. This assemblage occurs in wave-reworked compound-dune bottomsets and interdune areas of the compound-dune field.

Cruziana-Rusophycus Assemblage

This association occurs on the soles of wavy- (H_1) and lenticular-bedded (H_2), ripple cross- (**S_R**) and planar-laminated (**S_L**) sandstones of facies association 3 and 4. Trace-fossil density is moderately low to moderately high, and ichnodiversity is highly variable, ranging from low to high. Although the most common ichnofossil in this assemblage is *Planolites montanus*, other subordinate and rare components are cf. *Asterosoma* isp*., Cheiichnus gothicus, Cruziana pectinata, Helminthopsis hieroglyphica, Palaeophycus tubularis, Rusophycus jenningsi* and *Rusophycus pectinatus*. The resident benthic ichnofauna included worm-like animals such as polychaetes and nematodes, but also included arthropods. Many different trophic types, including predators and deposit feeders, would have been part of this mobile benthic assemblage. Integration of sedimentologic and ichnologic information suggests fluctuating oxygenation, normal salinity, and an abundant food supply in a low-energy environment. This K-selected climax community represented in this assemblage indicates a well-established colonization window. The associated facies signify deposition of small-scale, tidally generated bedforms and suspension fallout in compound-dune bottomsets and interdune areas that have been subsequently affected by wave reworking.

Palaeophycus Assemblage

This association is dominantly found in planar cross-stratified (**S_P**) and planar-laminated (**S_L**) fine- to medium-grained sandstone of facies association 2. Density of trace fossils is low to

moderate and ichnodiversity is moderately low. The assemblage is dominated by *Palaeophycus tubularis*, with subordinate occurrences of *Skolithos linearis* and rare *Halopoa* isp. The benthic community was composed of worm-like animals (e.g. polychaetes) and dominated by mobile predators and suspension feeders, with less participation of mobile elements. Deposit feeders were rare. The trace fossils present in this community reflect good oxygenation, normal salinity, low to moderately high energy and abundant food supply. The associated facies reflect bed-load deposition of 2D dunes in a compound-dune field.

Cheiichnus-Halopoa Assemblage

This association occurs in wavy-bedded (H_1) and ripple cross-laminated (**S_R**) sandstone of facies associations 3. Trace-fossil density is moderate and ichnodiversity is high. The assemblage is dominated by *Planolites montanus*, and *Palaeophycus tubularis* and *Skolithos linearis* are also abundant. *Asterosoma* isp.*, Cheiichnus gothicus, Halopoa* isp*,* and *Helminthopsis hieroglyphica* are rare. The resident benthic fauna comprises both sessile and mobile elements and is inferred to have included worm-like organisms, such as polychaetes, as well as arthropods. Many different trophic types, including predators, deposit and suspension feeders, were present. Integration of sedimentologic and ichnologic information suggests tidally influenced marine conditions with good oxygenation, normal salinity, low to moderate energy and abundant food supply, both in the sediment and the water column. Brief periods of anoxia are recorded by the presence of unbioturbated black mudstone intervals. The colonization window was sufficient to allow for a K-selected climax community to develop. The associated facies are representative of the migration of small bedforms in wave-reworked compound-dune bottomsets.

Skolithos Assemblage

This assemblage occurs on bed tops in sigmoidal shaped (**S_{SIG}**) and trough cross stratified (**S_T**) fine- to coarse-grained sandstone of facies association 1. Density of trace fossils ranges from moderate to high. The *Skolithos* assemblage is a monospecific assemblage composed solely of *S.linearis*. This assemblage is dominated by the activity of worm-like organisms, such as polychaetes (Alpert, 1974). The benthic community was dominated by sessile, suspension feeders, taking advantage of the abundant food particles in the well-oxygenated water column of a shallow-marine environment. Due to the high energy and stressed conditions of the area, a brief colonization window was available, as such an r-selected community was able to opportunistically colonize the sediment (e.g., Vossler and Pemberton, 1988; Pemberton et al., 1992), immediately after tidal-dune migration. The associated facies represent shifting 3D dunes in a compound-dune field experiencing high sedimentation levels deposited through bed-load deposition.

Skolithos-Palaeophycus Assemblage

This assemblage usually occurs on the tops of bioturbated sandstone ($\mathbf{S_B}$) beds of facies association 1, and is characterized by moderate density and low diversity. The assemblage is dominated by *Skolithos linearis*, with subordinate occurrences of *Palaeophycus tubularis*. The community in the area was dominated by predatory and suspension-feeder polychaetes, phoronids and other worm-like organisms. Environmental conditions were typified by good oxygenation, normal marine salinity, high energy and abundant food particles suspension. Due to the limited colonization window and instability of benthic conditions, an r-selected community was favoured. The facies associated with this assemblage represent shifting 2D dunes experiencing high-sedimentation rates in the compound-dune field.

5 Arthropod Trace Fossils in the Addy Quartzite

Arthropod trace fossils in the Addy Quartzite are represented by *Cheiichus gothicus, Cruziana pectinata, Rusophycus jenningsi*, and *Rusophycus pectinatus*. These arthropod trace fossils are rare in both diversity and density. They occur dominantly on the soles of ripple cross- and planar-laminated sandstones, which are found in wavy and lenticular bedded heterolithic units. These facies are also associated with wave-rippled and laminated siltstone facies. The facies are components of facies associations 3 and 4, which indicate wave-reworked compound-dune bottomsets and interdune areas, respectively, in the compound-dune field.

The Addy arthropod trace fossils reflect the activity of a resident, mobile, benthic community expressing a dominance of K-selected organisms. This type of fauna is favoured by a lengthy colonization window experiencing periodic sand sedimentation, with relatively stable conditions such that varied and complex, inter- and intraspecific relationships would have been established. Facies evidence shows a preference for these animals to inhabit areas of moderately-low to moderate energy, while taking advantage of and exploiting for food deposition of finer grained siltstone intervals.

The arthropod trace fossils in the Addy Quartzite favour comparisons with ichnofaunas from coeval units, formed as a result of similar depositional processes. Units with similar ichnologic and sedimentologic expression include the Gog Group of western Canada (Desjardins et al., 2010), the Gypsy Quartzite of southeast Washington (Lindsey et al., 1990), and the Brigham Group of Utah (Podrebarac, 1976).

6 Trace fossils and biostratigraphy

A number of trace fossils present in the Addy Quartzite may bear biostratigraphic significance. This is particularly true of trilobite trace fossils. As noted by Seilacher (1970, 1992, 1994), trilobite structures can preserve specific fingerprints of their producers, enhancing their potential in biostratigraphy.

For example, *Cruziana pectinata*, *Rusophycus pectinatus* and *Rusophycus jenningsi* have been originally described from the Lower Cambrian (Stage 3) Lake Louise Formation of the Gog Group in the Canadian Rockies (Seilacher, 1994; Desjardins et al., 2010, in press). Jensen et al. (2002) documented a rusophyciform *Cruziana* cf. *pectinata* (i.e. *Rusophycus* cf. *pectinatus*) from Cambrian Stage 3 strata included in the Upper Member of Wood Canyon Formation, in the western United States. Recently, Desai et al. (2010) recorded a rusophyciform *Cruziana pectinata* from Cambrian Stage 4 of the Shale Member of the Koti Dhaman Formation, Tal Group, in India. However, this form lacks the diagnostic features of *C. pectinata*, and should be removed from this ichnotaxon.

Rusophycus jenningsi was introduced based on material from the Lake Louise Formation of the Gog Group (Fenton and Fenton, 1937). In addition to its occurrence in western North America, this ichnospecies has also been recorded in the Cambrian Montezuman Stage strata of the Mickwitzia Sandstone in central Sweden (Jensen, 1997).

Another ichnotaxon known from the Gog Group, the Addy Quartzite, and the Mickwitzia Sandstone is *Cheiichnus gothicus* (Desjardins et al., 2010, in press; Jensen and Bergström, 2000). In addition, this ichnospecies has been recorded also in the Grammajukku Formation of northern Sweden, a unit of Cambrian Stage 2 to 3 age **(**Moczydłowska et al., 2001). While *C. pectinata* and *R. pectinatus* are only known from the western margin of Laurentia, *R. jenningsi* and *C. gothicus* also occur in Baltica. The stratigraphic range of this arthropod trace-fossil assemblage seems to be Cambrian Stage 2 to 4.

Interestingly, the worm radial trace *Dactyloidites* also seems to display a restricted stratigraphic range during the Cambrian. As recently noted by Jensen et al. (in review), the global distribution of *Dactyloidites* in Laurentia, Avalon and Gondwana suggests a cosmopolitan form. All well-dated recordings of *Dactyloidites* are from the Cambrian Montezuman Stage.

7 Evolutionary Paleoecology

The Addy Quartzite reflects a dynamic shift in evolutionary paleoecology. The trace fossils found in this unit clearly show a coupling between the benthic and planktonic realm of shallow-marine communities (see Mángano and Buatois, 2007). This is a reflection of the advanced phase of the Cambrian agronomic revolution. The Addy ichnofauna differs from other ichnofaunas of the initial phase of the agronomic revolution in that there is the inclusion of a vertical trace fossil

component, a wider range of arthropod-produced trace fossils, and more efficient use of endobenthic ecospace by a wider variety of trophic types which are establishing several different communities in several different environments.
The degree and depth of bioturbation within the Addy also reflects the Cambrian agronomic revolution. Although there is a significant component of horizontal, bedding-plane trace fossils, the inclusion of mid- to deep-tier vertical trace fossils shows an increase in infaunalization and thus an increase in the complexity of the benthic community (Mángano and Buatois, 2004). Dense monospecific assemblages of *Skolithos linearis* piperocks are found in the Addy Quartzite indicating an increase in complexity of food procurement strategies and a more efficient use of endobenthic ecospace (Mángano and Buatois, 2004).
Sedimentary features of the Addy Quartzite indicate a dynamic benthic community. The most dense and diverse trace-fossil assemblages occur within the heterolithic facies assemblages. The *Cheiichnus-Halopoa*, *Cruziana-Rusophycus*, and *Helminthopsis-Planolites* trace-fossil assemblages are hosted in facies assemblages 3 and 4. This reflects an r-selected community established in wave-reworked compound-dune bottomsets and interdunes. These are the only environments that host arthropod trace fossils, and are dominated by shallow and mid-tier trace fossils. The lowest diversity of trace fossils is found in the sand dominated facies associations 1 and 2. These facies associations reflect migration of 3D and 2D dunes within the compound dune field. A K-selected, opportunistic community was dominant here and no arthropod trace fossils are found within these facies associations.
Although microbial mats are present in the Addy Quartzite, trace fossils are very rarely associated with them. This suggests that the mat-ground ecology that typified the Ediacaran and earliest Cambrian has been replaced by a mix-ground ecology by the late Early Cambrian.

8 Conclusions

The Addy Quartzite provides new insight into the evolution of benthic communities along the paleocoast of the Wyoming Craton during the Early Cambrian. This is the first study that integrates ichnologic, sedimentologic and paleoenvironmental data, in order to evaluate all ecological aspects during deposition of the Addy Quartzite has. This formation forms a distinctive tide-dominated succession through much of the northeastern part of Washington State. Sedimentologic analysis recorded 12 sedimentary facies, grouped into 5 facies associations. These facies associations clearly show tidally influenced depositional environments, specifically the establishment of a compound-dune field composed of 3D and 2D dunes, as well as wave-reworked compound-dune bottomsets and interdune areas.
Eleven different trace fossils are recognized from the Addy Quartzite. These trace fossils can be grouped into six ichnological assemblages which are in turn linked to the sedimentary facies association. Ichnologic information provides additional data on the specific depositional

conditions based on the information of the type of trace maker and their respective life strategies. Integrated sedimentologic, ichnologic and paleoenvironmental data indicate specific ecological conditions at the time of Addy deposition. The data indicates a diverse and well-established climax community inhabited both the compound-dune bottomsets and interdune areas. These areas favour trace-fossil preservation in the sandy units, although the silty units also host trace fossils produced by mobile deposit-feeding organisms. An opportunistic community consisting dominantly of trace fossils reflecting suspension-feeding organisms is favoured in the sandy units of the compound-dune field.

The ichnologic data also adds information on the evolutionary paleoecology during the time of Addy deposition, allowing for a more clear designation of the importance of tide-dominated shallow-marine settings and their role in hosting the benthic fauna of the Cambrian agronomic revolution. The presence of microbial matgrounds coupled with a lack of associated trace fossils clearly indicates that the agronomic revolution was well underway, supporting the notion of a coupling between the benthos and plankton.

References

Alpert, S.P., 1974, Systematic review of the genus *Skolithos*. Journal of paleontology, v. 48, iss. 4, p. 661-669.

Baldwin, C.T., 1977, Internal structures of trilobite trace fossils indicative of an open surface furrow origin. Palaeogeography, Palaeoclimatology, Palaeoecology, v.21, p.272-284.

Baldwin, C.T., 1978, A comparison of the stratigraphy and depositional processes in the Cambro-Ordovician rocks of the Cantaabrian and West Asturian-Leonese Zones, N.W. Spain. Brevoria Geologica Asturica, Special Publication 27, p. 44-70.

Becraft, G.E. and Weis, P.L., 1963, Geology and mineral deposits of the Turtle Lake quadrangle, Washington. U.S. Geological Survey Bulletin 1131, p. 73.

Bennett, W.A.G., 1941, Preliminary report on Magnesite Deposits of Stevens County, Washington. Washington Division of Geology Report of Investigations, no.5, p.25

Bergstrom, J., 1969, Remarks on the appendages of Trilobites. Lethaia, v.2, pp.395-414.

Bromley, R.G., 1996, Trace Fossils- biology, taphonomy and applications (2nd ed.). Chapman and Hall, London, UK.

Campbell, I., and Loufburrow, J.S., Jr., 1962, Geology of the Magnesite belt of Stevens County, Washington. U.S. Geological Survey Bulletin 1142-F, p.F1-F53.

Cattaneo, A., and Steel, R.J., 2003, Transgressive deposits: A review of their variability. Earth-Science Review, v. 62, p. 187-228.

Crimes, T.P., 1968, *Cruziana*: A stratigraphically useful trace fossil. Geological Magazine, v. 105, no. 4, pp.360-364.

Crimes, T.P., 1969, Trace fossils from the Cambro-Ordovician of North Wales and their stratigraphic significance. Geologic Journal, v.6, p. 333-338.

Crimes, T.P., 1975, The stratigraphic significance of trace fossils. In: Frey, R.W., ed., The study of trace fossils. Springer Verlag, new York, NY, United States (USA), p. 109-130.

Crimes, T.P. and Marcos, A., 1976, Trilobite traces and the age of the lowest part of the Ordovician reference section for N.W. Spain. Geological Journal, Special Issue 9, p.91-138.

Dalrymple, R.W., 1992, Tidal Depositional Systems. In: (eds.) Walker, R.G. and James, N.P. *Facies Models: A response to sea level change*. Geological Association of Canada, Geo Text 1, Canada, p. 195-218.

Desjardins, P.R., Pratt, B., Buatois, L.A. and Mángano, M.G., 2010, Stratigraphy and sedimentary environments of the Lower Cambrian Gog Group in the southern Rocky Mountains of western Canada: Evolution of transgressive sandstones on a broad continental margin. Bulletin of Canadian Petroleum Geology, v. 58, p. 403-439.

Desjardins, P.R., Buatois, L.A., Pratt, B.R. and Mangano, M.G., in press, Sedimentological–ichnological model for tide-dominated shelf sandbodies: Lower Cambrian Gog Group of western Canada. Sedimentology.

Droser, M.L., Jensen, S., and Gehling, J.G. 2004. Development of early Palaeozoic ichnofabrics: evidence from shallow marine siliciclastics. In: (ed.) McIlroy, D. *The Application of Ichnology to Paleoenvironmental and Stratigraphic Analysis*. Geological Society, London, Special Publications, 228, pp. 383-396.

Droser, M.L. and Li, X. 2001. The Cambrian Radiation and the Diversification of Sedimentary Fabrics. In: (eds.) Zhuravlev, A. and Riding, R. *The Ecology of the Cambrian Radiation*. Columbia University Press, New York, pp. 137-169.

Dutro, J.T., and Gilmour, E.H., 1989, Paleozoic and Lower Triassic biostratigraphy of northeastern Washington, in, Joseph, N.L., ed., Geologic Guidebook for Washington and adjacent areas: Information Circular- State of Washington, Department of Natural resources, Division of Geology and Earth Resources, Report, v. 86, p. 23-39.

Evans, J.G., 1987, Geology of the Stensgar Mountain Quadrangle, Stevens County, Washington: Stratigraphy and Structure of the Proterozoic and Lower Cambrian Rocks. U.S. Geological Survey Bulletin, no.1679, 23pgs.

Evans, J.G., 1988, Deformation in the Stensgar Mountain Quadrangle, Stevens County, Washington. U.S. Geological Survey Bulletin, no.1820, 30pgs.

Fenton, C.L. and Fenton, M.A., 1937, Trilobite "nests" and feeding burrows. American Midland Naturalist, v. 18, pp.446-451.

Fillion, D., and Pickerill, R.K., 1990, Ichnology of the Upper Cambrian? To Lower Ordovician Bell island and Wabana groups of eastern Newfoundland, Canada. Palaeontographica Canadiana, v. 7, p. 117.

Fortey, R.A. and Owens, R.M., 1999, Feeding habits in trilobites. Palaeontology, v. 42, p. 429-465.

Gail, A.M., 1990, Classification of Large-Scale Subaqueous Bedforms: A New Look at an Old Problem: SEPM Bedforms and Bedding Structures. Journal of Sedimentary Petrology, v.60, no.1, p.160-172.

Han, Y., and Pickerill, R.K., 1995, Taxonomic review of the ichnogenus *Helminthopsis* Heer 1877 with a statistical analysis of selected ichnospecies. Ichnos, v. 4, iss. 2, p. 83-118.

Hollingsworth, J.S., 2005, The earliest occurrence of trilobites and brachiopods in the Cambrian of Laurentia. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 220, p. 153-165.

Hollingsworth, J.S., 2006, Holmiidae (Trilobita: Olenellina) of the Montezuman State (Early Cambrian) in western Nevada. Journal of Paleontology, v. 80, p. 309-333.

Jensen, S., 1990, Predation by early Cambrian trilobites on infaunal worms - evidence from the Swedish Mickwitzia Sandstone. Lethaia, v. 23, p. 29-42.

Jensen, S. 1997, Trace Fossils from the Lower Cambrian Mickwitzia sandstone, south-central Sweden. Fossils and Strata, no. 42.

Jensen, S. and Bergstrom, J., 2000, *Cheiichnus gothicus* igen. Et isp. N., a new Bergaueria-like arthropod trace fossil from the Lower Cambrian of Vastergotland, Sweden. GFF, v.122, pt.3, pp. 293-296.

Jensen, S., Droser, M.L. and Heim, N.A., 2002, Trace fossils and ichnofabrics of the Lower Cambrian Wood Canyon Formation, southwest Death Valley area. In: Corsetti, F.A. (ed.), *Proterozoic-Cambrian of the Great Basin and Beyond*. Pacific Section SEPM Volume and Guidebook 93, p. 123-135.

Jensen, S., Buatois, L.A. and Mángano, in review, Palaeogeographical patterns in the distribution of Cambrian trace fossils. In: Dave Harper and Thomas Servais (Eds.), *Early Palaeozoic Palaeobiogeography and Palaeogeography*. Geological Society of London Memoir.

Lindsey, K.A. and Gaylord, D.R., 1992, Fluvial, coastal, nearshore, and shelf deposition in the upper Proterozoic (?) to Lower Cambrian Addy Quartzite, northeastern Washington: Sedimentary Geology, v. 77, p. 15-35.

Lindsey, K.A., Gaylord, D.R. and Groffman, L.H., 1988, Late Proterozoic to Cambrian sedimentology and stratigraphy of northeastern Washington; implications for rifting and

passive margin sedimentation: Geological Society of America, Abstracts with Programs, v. 20, pp. 402.
Lindsey, K.A., Gaylord, D.R. and Groffman, L.H., 1990, Geology of the Upper Proterozoic to lower Cambrian Three Sisters Formation, Gypsy Quartzite, and Addy Quartzite, Stevens and Pend Oreille Counties, northeastern Washington: Washington Division of Geology and Earth Resources, Report of Investigations, v. 30, p. 1-37.
Lucas, H.E., 1980, Geology of Part of the Dunn Mountain and Arden $7^{1/2}$ Minute Quadrangles, Stevens County, Washington. Thesis, Eastern Washington University. Cheney, Washington.
Magwood, J.P.A. and Pemberton, S.G., 1990, Stratigraphic significance of *Cruziana*: New data concerning the Cambrian-Ordovician ichnostratigraphic paradigm. Geology, v.18, pp.729-732.
Mangano, M.G., Buatois, L.A. and Acenolaza, G.F., 1996, Trace fossils and sedimentary facies from a Late Cambrian-Early Ordovician tide-dominated shelf (Santa Rosita Formation, northwest Argentina): Implications for ichnofacies models of shallow marine successions. Ichnos, v.5, pp.53-88.
Mangano, M.G., and Buatois, L.A., 2004, Terminal Proterozoic-Early Cambrian ecosystems; Ichnology of the Puncoviscana Formation, northwest Argentina. Fossils and Strata, v. 51, p.1-16.
Mangano, M.G. and Droser, M.L., 2004, The ichnologic record of the Ordovician radiation. In: The great Ordovician biodiversification event. Columbia University Press, New York, NY, United States (USA), p. 369-379.
Mansy, J.L., Gabrielse, H., 1978, Stratigraphy, terminology and correlation of upper Proterozoic rocks in Omineca and Cassiar mountains, North-central British Columbia. Geological Survey of Canada, iss. 77-19, p. 1-17.
Manton, S.M., 1977, The Arthropoda, Habits, Functional Morphology and Evolution. Clarendon, Oxford.
McLaughlin, K.P. and Enbysk, B.B., 1950, Middle-Cambrian Trilobites from Pend Oreille County, Washington: Journal of Paleontology, v. 24, p. 466-471.
Miller, F.K., and Clark, L.D.,1975, Geology of the Chewelah-Loon Lake Area, Stevens and Spokane Counties, Washington. U.S. Geological Survey Professional Paper, no.806, p.74.
Moczydlowska, M., Jensen, S., Ebbestad, J.O.R., Budd, G.E., marti-Mus, M, 2001, Biochronology of the autochthonous Lower Cambrian in the Laisvall-Storuman area, Swedish Caledonides. Geological Magazine, v. 138, iss. 4, p.435-453.
Moreno, F., Vegas, R., and Marcos, A., 1976, The age of the Ordovician and Cambrian series related to the Sardica Discordancy in the Valdelacasa Anticline, Montes de Toledo, Spain. Breviora Geologica Asturica, v. 20, iss.1 , p.8-16.
Okulitch, V.J., 1951, A Lower Cambrian Fossil Locality Near Addy, Washington: Journal of Paleontology, v. 25, p. 405-407.
Park, C.F., Jr., and Cannon, R.S., Jr., 1943, Geology and Ore deposits of the Metaline quadrangle, Washington. U.S. Geological Survey Professional Paper 202, 81pgs.
Patel, S.J., Desai, B.G., Shukla, R., 2009, Paleoecological significance of the trace fossils of Dhosa oolite member (Jumara Formation), Jhura Dome, mainland Kachchh, western India. Journal of the Geological Society of India, v. 74, n. 5, p. 601-614.
Pechenik, J.A., 2005, Biology of the Invertebrates (5^{th} ed.) McGraw Hill, New York, NY, United States (USA), p. 329-338.

Pemberton, S.G. and Frey, R.W., 1982, Trace fossil nomenclature and the *Planolites-Palaeophycus* dilemma. Journal of Paleontology, v. 56, iss. 4, p. 843-881.
Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I.K., 2001, Ichnology and sedimentology of shallow to marginal marine systems: Ben Nevis and Avalon reservoirs, Jeanne d'Arc basin. Geological Association of Canada, Short Course Notes, v. 15
Pickerill, R.K., and Fillion, D., 1983, On the Tremadoc-Arenig and Lower-Upper Tremadoc boundaries in the Bell Island Group, Conception Bay, eastern Newfoundland. Maritime Sediments and Atlantic Geology, v. 19, p. 21-30.
Pickerill, R.K., Romano, M., and Melendez, B., 1984, Arenig trace fossils from the Salamanca area, western Spain. Geological Journal, v. 9, p. 249-269.
Podrebarac, T., 1976, Trace fossils of the Brigham Quartzite (Lower and Middle Cambrian) in northern Utah and southeastern Idaho. MSc. Thesis, United States (USA).
Reesor, J.E., 1957, The Proterozoic of the Cordillera in southeastern British Columbia and southwestern Alberta. Royal Society of Canada Special Publications, v.2, pp150-177.
Romano, M., 1982, The Ordovician biostratigraphy of Portugal- A review with new data and reappraisal. Geological journal, v. 17, p. 89-110.
Rowell, A.J., 1977. Early Cambrian brachiopods from the southwestern Great Basin of California and Nevada. Journal of Paleontology, v. 51, p. 68-86.
Schlirf, M., and Uchman, A., 2005, Revision of the ichnogenus *Sabellarifex* Richter, 1921 and its relationship to *Skolithos* Haldeman, 1840 and *Polykladichnus* Fursich, 1981. Journal of Systematic Palaeontology, v. 3, iss. 2, p. 115-131.
Seilacher, A., 1964, Biogenic sedimentary structures. In: *Approaches to Paleoecology.* John Wiley and Sons, Inc., New York, NY, United States (USA).
Seilacher, A., 1970, *Cruziana* stratigraphy of "non-fossiliferous" Paleozoic sandstones. In: Crimes T.P., Harper J.C. (eds.), *Trace Fossils*. Geologic Journal Special Issue, v.3, pp.447-476.
Seilacher, A., 1985, Trilobite palaeobiology and substrate relationships. Transactions of the Royal Society of Edinburgh, v.76, pp.231-237.
Seilacher, A., 1990, Paleozoic trace fossils. In: Said, R. (ed.) *The Geology of Egypt*. Balkema, Rotterdam, pp.1565-1581.
Seilacher, A., 1994, How Valid is *Cruziana* Stratigraphy?. Geol Rundsch, v. 83, pp.752-758.
Seilacher, A., 2007, Trace Fossil Analysis. Springer-Verlag, Berlin, Germany.
Seilacher, A. and Pflüger, F., 1994, From biomats to benthic agriculture: A biohistoric revolution. In: ed. W.E. Krumbein, D.M. Peterson and L.J. Stal, *Biostabilization of sediments*. Bibliotheks und Informationssystem der Carl von Ossietzky Universität Odenburg, p. 97-105.
Taylor and Goldring, 1993, Description and analysis of bioturbation and ichnofabric. Journal of the Geological Society of London, v.150, iss. 1, p. 141-148.
Teichert, C., (ed.), 1989, Treatise on Invertebrate Paleontology. The University of Kansas and The Geological Society of America, Inc., Lawrence Kansas, U.S.A.
Uchman, A., 1998, Taxonomy and ethology of flysch trace fossils; revision of the Marian Ksiazkiewicz Collection and studies of complementary material. Annales Societatis Geologorum Ploniae, v. 68, p. 105-218.

Uchman, A., and Pervesler, P., 2007, Paleobiological and paleoenvironmental significance of the Pliocene trace fossil *Dactyloidites peniculus*. Acta Palaeontologica Polonica, v. 52, iss. 4, p. 799-808.

Weaver, C.E., 1920, The Mineral Resources of Stevens County. Washington Geological Survey, Bulletin no.20, p. 350

Wetzel, A. and Bromley, R.G., 1998, Re-evaluation of the ichnogenus *Helminthopsis*; a new look at the type material. Palaeontology, v. 39, p. 1-19.